The cities are becoming increasingly larger and more complex. This also determines increased requirements on mass transit systems. In this case, the operators have to cope with rapidly growing traffic flows and passengers' rising expectations. Their success is measured against factors such as safety, punctuality, convenience and energy efficiency. In order to successfully meeting these challenges, it is necessary to consider the Intelligent and future-oriented mass transit solutions. The aim of this work is to compare the performances between two types of subway, traditional ones and the automatic ones considering in one case the Line 1 and Line 5 to Milan.

**Keywords**—driveless subway; automation control systems; automatic train operation

I. INTRODUCTION

The subway is a transport system for short distances. Usually it extends into a big city and can go up to neighboring countries [1]. Despite the high initial cost, the subway allows to transport a large number of passengers in a short time because it usually is not built on the road surface and allows to reduce the traffic on the surface [2, 3].

In general, it can be said that the automatic subway is the daughter of two technologies created in different areas that are developed and then merged together. In fact, if the subway is, simplistically, a short railroad used in urban areas, the automatic driving is the son of the need of the railways to use more machines to tow the same convoy, in particular for heavy goods trains, without that each should have a driver on board. This is the technology of multiple command, remote control used now for all train sets either, and many double traction freight trains (usually not in control multiple machines in line) [4-6].

The scope of this work will be to make a comparison of different aspects of traditional and automatic subway. In this case, the comparison will be to consider respectively the Line 1 (traditional subway) and Line 5 (automatic subway) present in Milan (Italy).

II. DIFFERENT POINTS OF SUBWAY SYSTEM AUTOMATION

In traditional subway trains are operated by human drivers usually assisted by a signaling system [7, 8]. This means that the driver drives the metro train on sight, while at the same time the railway operation is controlled through stationary light indicators. Usually trains are also equipped with a train-stop and an overspeed protection system that call emergency braking in case of driver sudden illness or mistake. Traffic regulation is demanded to driver, assisted by Central Control Room indications, dispatched through stationary indicators lights and radio communications. Usually traditional undergrounds have rolling stock of “heavy” type (about 100 m long with a passengers capacity of about 1200) passenger and are usually operated with headways of about 120 – 180 s.

The term “automatic” is often associated with the meaning “without driver”. However, this is not totally correct because different levels of subway system automation can be identified, ranging from automatic speed control systems, driver-assisting function for brake control, remote control systems to automatically regulate the stops at subway stations and the opening/closing of the subway’s doors, to full spectrum automatization of driverless subway operation.

There are different situations:

- Supervision and Control Train Operation (SCO) is a partly automated mode;
- Semi-automated Train Operation (STO) is a semi-automated mode;
- Driverless Train Operation (DTO) is a driverless mode;
- Unattended Train Operation (UTO). In this last case, the train is also controlled and monitored automatically.

There are different advantages adopting the driverless metros, and in particular:

- Train can run more frequently and so the subway can transport the same quantity of people with shorter trains and, consequentially, smaller stations;
- Service frequency can easily be adjusted to meet sudden unexpected demands because the lack of drivers allows to put in service or out of service trains in a short time;
- Train turnover time at terminal can be extremely short reducing the number of train sets needed for operation;
- Train can run really closer each other allowing a better management of delays;
- Financial savings in both energy and wear and tear costs because train are driven to an optimum specification;
- Lower expenditure for staff (or optimized use of staff).

From the safety point of view, Automatic Metros have specific automated system to prevent every danger that can occur during the operation of line. These automatic systems are
projected in order to achieve high reliability, according to specific safety analysis and they are not affected by human errors.

Obviously, this has some criticism for example despite the theoretical safeness of automated systems, some passengers might still have safety concerns or be afraid of trains that seem to run by themselves; the conversion of traditional metros into driverless ones puts train drivers out work.

III. AUTOMATION SYSTEMS FOR AUTOMATIC URBAN SUBWAY

In order to have a fully automatic management to be carried out with high degree of safety, it is necessary to require a set of functions interacting with each other:

- Moving Train
- Handling of the passengers
- Centralized Management

The performance of mass transit systems depends largely on the performance of the Automatic Train Control (ATC) system employed. With increasing automation, the responsibility for operations management gradually shifts from drivers and operators to the system. The ATC system usually comprises different functions, in particular for the monitoring, the execution and the control of the entire operational process. It can feature different levels of automation, in particular driver-controlled train operation, semi-automated train operation, driverless and unattended train operation. The ATC system continuously indicates the current movement authority on the cab display and supervises the permissible train speed. Color light signals are therefore no longer required. ATC can also be used with Automatic Train Operation (ATO) and is usually considered safety-critical part of the system. Over time, there have been different safety systems labeled as "automatic train control". Usually ATC system is divided into three subsystems:

- **ATP**: Automatic train protection

  It uses a target speed indication and audible warnings to warn the train driver – when present – if they are likely to exceed a speed profile that will cause the train to pass a red (danger) signal or exceed a speed restriction. In this case, the system applies emergency braking if the driver fails to respond to these warnings. The system takes into account, respectively of the speed and the position of the train. The system is given permitted speed and location information from the track via encoded balises, encoded track circuits, or more recently via radio signals.

- **ATO**: Automatic train operation

  It is an operational safety enhancement device used to help automate operations of trains. Usually, it is used on automated guideway transits and subways, which are easier to ensure safety of humans. Most systems elect to maintain a driver in order to mitigate risks associated with failures or emergencies.

- **ATS**: Automatic train supervision systems

  The control system provides different information, in particular a wide range of proven train tracking, route setting and dispatcher-level functions from the local operator console to the highly automated centralized supervision and control centers. The ATS also regulate train behavior in order to manage delays and time schedules.

In Figure 1 are reported the different automatic train control systems that they provide the integrated data management for the automatic unmanned operation and support the efficient procedures.

![Fig. 1. Integrated Control System [7]](image_url)

IV. DETAILED TRAIN AND STATION EQUIPMENT

Driverless subways respond to customer requirements by introducing special safety infrastructures, such as platform screen doors and by automating and improving systems existing in traditional metro lines, such as audio signals, and fire detection systems. From the train movement point of view the safety system already existing in traditional metros are managed by the automatic train control, such as emergency brake systems. New automatic functions are implemented in order to manage all travel parameters, such as speed control and door control and monitoring system. These metro trains can be regarded as particularly safe and technically advanced if compared to traditional trains with human driver. What is more, careful attention is paid to configure safety systems in a careful and redundant way so that the back up system pitches in automatically in case of failure.

Driverless metros are endowed with a particular obstacle detection feature that automatically starts the breaking process as soon as an obstacle is detected. They are also equipped with special derailment detectors that, in case of derailment, automatically detect the derailed vehicle, securely stop the metro and report the incident to an operations control center.

The cutting-edge safety feature in modern subway consists of transparent doors that separate rail tracks from platforms. Train doors and platform doors are aligned and open simultaneously after the train has stopped. Subway systems with Platform Screen Doors (PSD) allow different advantages, especially the high security for the people. The benefits using this technology are [9]:

- Preventing people from falling or jumping on the tracks;
- Allowing trains to enter the stations at higher speed;
- Reducing draught and air pressure caused by trains;
• Letting platforms be quieter and cleaner;
• In hot climate, allowing the station to be air-conditioned at lower cost;
• Preventing people from throwing trash on the tracks and thus preventing track fires.

The platform doors used in driverless systems allow the management of arrival at stations, descent and boarding by passengers and departure from stations without driver: a specific set of sensors detects the state of doors and allows train movement (arrival and departure) only if doors are closed and locked.

This prevents from potential accidents due to the fall of people into the gap between the platform and the vehicle, and eases the entrance/exit procedures for people with reduced mobility or sight problems.

Door gap monitoring systems are in some case added to platform screen doors; they are capable of detecting even narrow and flexible bodies further help increase the level of safety. The train is not allowed to start off until all the doors are properly closed.

After the metro train starts moving all emergency door release systems are locked. Faults and emergency conditions (such as on-board emergency handles activation or fire detection) are automatically managed by the Automatic Train Operation system according to the principle that, if possible, trains should not stop along line, in order to privilege evacuation from station (usually possible without staff attendance).

In the unfortunate circumstance of a metro stopping in the tunnel for a disruption, all doors are kept locked until the operations control center has instructed the measures needed to ensure safety, such as stopping oncoming traffic and switching off the power supply to the power rail. In some cases additional tunnel emergency lighting is activated automatically or by central operators when the traction current in the tunnel is switched off.

In case of fire on board, along line or in stations automatic underground are equipped with a wide range of detectors that are able to detect and locate the problem; instantly an alarm is sent to the control center room where an automatic system propose to the operator a strategy for manage fire and smoke and for passenger evacuation. At the same time ATC system manages trains avoiding the approaching ones to enter the emergency zone and trying to lead the ones in the emergency zone to the nearest station for an easy and safe evacuation of on-board passenger.

V. TRADITIONAL URBAN SUBWAY: LINE 1

The Subway Line 1 is the first underground rapid transit line built in Milan Italy (the first part of the line from Sesto Marelli to Lotto was opened the first November 1964) and it is considered a traditional subway (Fig. 2) because it had “heavy” type rolling stock and driver on board. The safety of trains was managed by a signaling system that controlled crossover and stationary indicators for the communication of line speeds and permissions to driver on-board. The rolling stock was also equipped with a train stop and an over speed protection system.

Today, this line has undergone a modernization of the signaling system and now the line is operated with presence of driver on board with limited tasks in normal operation (substantially stop in parking management, opening and closing door); it remains unchanged type and size of rolling stock and stations.

In this work, the attention is on the extension from Sesto to Monza and in particular, we will focus on power demand for electrical traction and potential of the line in terms of sustainable clocking in critical hours.

A. Number, distribution and dimensioning of electrical substations

This extension will be developed by the end of the maneuvering station Sesto FS until the station Cinisello Monza, with its operating rod. The extension extends for 2,260 m and includes the stations named: Sesto Restellone and Cinisello Monza.

Today, the vehicles that run in Line 1 of Milan have relevant innovations from the electrical point of view, such as the introduction power-up chopper of the motors and the conditioning railway carriages, with consequent change in the values and in the mode of current absorption respect to older ones (Fig. 3). The main new train characteristics relevant for traction dimensioning are summarized in Table I.

<table>
<thead>
<tr>
<th>Information</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>105</td>
<td>[m]</td>
</tr>
<tr>
<td>Mass (fully loaded)</td>
<td>268542</td>
<td>[kg]</td>
</tr>
<tr>
<td>Weight (fully loaded)</td>
<td>2631714</td>
<td>[N]</td>
</tr>
<tr>
<td>Train composition (M = motor, R = trailer)</td>
<td>M – R – M – M – R – M</td>
<td>-</td>
</tr>
<tr>
<td>Hourly power (each engine is equipped with 4 engines with hourly output of 108 kW)</td>
<td>1728</td>
<td>[kW]</td>
</tr>
</tbody>
</table>
### Maximum Power
- **Maximum power**: 2700 kW
- **Full speed**: 80 km/h
- **Mean acceleration starter**: 0.8 m/s²
- **Average deceleration service**: 1 m/s²
- **Average deceleration emergency**: 1.9 m/s²
- **Coefficient rotating masses**: 0.12
- **Rated voltage supply**: 750 V d.c.
- **Total return (mechanical and electrical)**: 78%
- **Maximum current consumption**: 3600 (*) A
- **Current consumption by auxiliary services, packaging, etc...**: 150 A

### Table II. Distance Between Different Substations

<table>
<thead>
<tr>
<th>SSE Distance [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between SSE Gorla and SSE Dep. Precotto</td>
</tr>
<tr>
<td>Between SSE Dep. Precotto and SSE Gramsci</td>
</tr>
<tr>
<td>Between SSE Gramsci and Cinisello Monza +SSE Bettola</td>
</tr>
<tr>
<td>Between End extension and Cinisello Monza +SSE Bettola</td>
</tr>
</tbody>
</table>

The mean distance between substations is about 1500 m in the part of the line with 90 s headway and about 2700 m in the part of the line with 180 s headway.

Each SSE is equipped with two groups of conversion da 3000 kW that always working together.

### B. Potential of the Line

The traditional signaling system (now no longer in service) of line 1 of Milan allows to reach a theoretical potential of the line corresponding to a timing of approximately 90 s in the central section. It should be noted that this timing is achievable thanks only to the fact that:

- In the west side, the line presents a rail junction (near Pagano station) that allows to split the traffic on two terminuses each one with two rails and maneuvering rod (thus have the potential of inversion that is equal to about 180 s),
- In the east side, the line now has a terminal with three tracks and platform, while for the future configuration prolonged in Monza it is foreseen that half of the trains will be clinched in Sesto and only the other half will reach the new terminal station (Monza).
In practice, however, it should be noted that the potential of the line indicated above is limited essentially by the time for turnback operations that is bound to train driver workbench change time.

VI. AUTOMATED URBAN SUBWAY: LINE 5

Many lines operate with ATO, with the aim of improving the frequency of service. The ATO technology has been developed to enable trains to operate without a driver. In particular, in this case, it is considered the automated urban subway system located in Milan and in particular the Line 5.

This Line 5 is long 12.8 kilometers. It is part of the Milan subway and is of service for the North-Eastern suburb of the city. The first stage of the line covered the 4.1 kilometers from Bignami to Zara. On 1 March 2014, it is opened for 1.9 km and the second stage from Zara to Garibaldi FS. The third stage, from Garibaldi FS to San Siro Stadio, long 7 km has been opened on April 2015 (Fig. 5).

Fig. 5. Integrated Control System

A. Number, distribution and dimensioning of electrical substations

The vehicles used for the automatic subway (Fig. 6) have the following characteristics:
- Wheel arrangement B0-B0-2-B0-B0
- Maximum speed: 80 km/h
- Length: 51 m
- Width: 2650 mm
- Empty weight: 79.39 kg x1000
- Passenger load (load C3): 37.52 kg x1000
- Weight full load (load C3): 116.91 kg x1000
- Rotating masses: 9.0 kg x1000
- Wheel Type: steel
- Wheels diameter (forward / medium / min) 711/686/661 mm
- Gear ratio 1/6.8235
- Reducer efficiency 0.97
- Average acceleration from 0 to 33 km/h is equal to 1.02 m/s²
- Mean deceleration of service from 80 km/h is 1.1 m/s²
- Average deceleration emergency from 80 km/h is 1.24 m/s²
- Mechanical and Electrodynamic braking systems

The third rail used for the project is made of aluminum with stainless steel cladding poorly subject to wear and ensures a constant electrical resistance over time. For the return circuit, the track used for the project is the type 50UNI3141.

Trains have an electrodynamic braking system managed by Electronic Control Units and used in cooperation with a traditional mechanical braking system. The blending between the two braking systems during deceleration is managed trying to maximize the electrodynamic braking. The electrodynamic braking energy is carried by the third rail and used for other trains acceleration, if possible; otherwise this energy is dissipated by onboard braking rheostat (the choice is based on line voltage growth evaluation in correspondence of decelerating train position). The theoretical project has done headway for traction dimensioning, in fact, the time is 75 seconds and in degraded conditions (with SSE inactive) the time can be equal to 120 seconds.

The mean distance between substations is about 1400 m.

The characteristics of the SSE Garibaldi FS - Bignami are the following:
- Rated voltage: 750 V
- Open circuit voltage: 800 V
- Rated Power: 2500 kW
- Rated current: 3333 A
- Number of rectifier: 1
- Type of rectifier: Twelve-pulse bridge, with parallel connection of the two six-pulse bridge and Coil interphase

For segment San Siro - Monumental are provided SSE higher power, whose characteristics are as follows:
- Rated voltage: 750 V
- Open circuit voltage: 800 V
- Rated Power: 3000 kW
- Rated current: 4000 A
- Number of rectifier: 1
Type of rectifier: Twelve-pulse bridge, with parallel connection of the two six-pulse bridge and Coil interphase.

The mean distance between substations is about 1400 m.
**Table III. SSE Positioning and Size**

<table>
<thead>
<tr>
<th>SSE</th>
<th>Distance from the SSE following [m]</th>
<th>Number of groups</th>
<th>Power [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>S. Siro Harar Dessié</td>
<td>852</td>
<td>1</td>
<td>3000</td>
</tr>
<tr>
<td>S. Siro Trotter</td>
<td>1278</td>
<td>1</td>
<td>3000</td>
</tr>
<tr>
<td>Lotto M1</td>
<td>2482</td>
<td>1</td>
<td>3000</td>
</tr>
<tr>
<td>Gerusalemme</td>
<td>1453</td>
<td>1</td>
<td>3000</td>
</tr>
<tr>
<td>Monumentale</td>
<td>598</td>
<td>1</td>
<td>3000</td>
</tr>
<tr>
<td>Garibaldi</td>
<td>1479</td>
<td>1</td>
<td>2500</td>
</tr>
<tr>
<td>Zara</td>
<td>1036</td>
<td>1</td>
<td>2500</td>
</tr>
<tr>
<td>Istria</td>
<td>1547</td>
<td>1</td>
<td>2500</td>
</tr>
<tr>
<td>Biccocca</td>
<td>1672</td>
<td>1</td>
<td>2500</td>
</tr>
<tr>
<td>Bignami</td>
<td>-</td>
<td>1</td>
<td>2500</td>
</tr>
</tbody>
</table>

**B. Potential of the Line**

The signaling system of Line 5 of the Milan allows to reach a theoretical potential of the line corresponding to a timing of approximately 75 s in line and of about 100 s for the automatic reversal to the terminuses. It should be noted that in practice the line today achieves such performance only in particular cases and occasions, in connection with the current sizing of the fleet of vehicles, which is designed for a timing entire line equal to 180 s.

**VII. CONCLUSIONS**

Milan has an extensive internal transport network and is an important transportation node in Italy, being one of the country's biggest hubs for air, rail and road networks. In this work, the attention is on the subway and in particular on Line 1 (traditional subway) and Line 5 (automatic subway).

The purpose of transportation system subway is to provide secure, consistent, efficient and high-quality service to passengers. As many operators run at or near their capacity limits, automation is often the only way to maximize the operational performance of a metro system.

Driverless trains are run by computer systems located in a remote control room, platform screen doors and many sensors watch the whole perimeter of automatic metro line zone, rise alarms and stop trains in case of danger.

The benefits of driverless metro systems seem to be obvious, in particular, trains can run more frequently and this means that it is possible to reach the same transport capability with shorter trains and smaller stations (with possible benefits in structural construction costs and impact in the city). Moreover driverless metro system have more predictable running times than traditional ones, the ATO system can manage trains with energy optimization, automated and computerized failure detection and automated emergency management improve passengers safety. On the other hand, automated systems are in many cases more cost-effective than traditional systems and also maintenance and future extentions of the line could be more cost effective. For a competitive industry looking to achieve gains in customer service and safety, one has to ask whether removing staff from the trains makes sense and can be justified.

**REFERENCES**


