UNDERSTANDING ZERO-EMISSION BUS MAINTENANCE

PART 1 – INTRODUCTION TO ZEBS

Funding partners:

Implementing agencies:
INTRODUCTION TO ELECTRIC BUSES
Air pollution
HISTORY: BATTERY POWERED VEHICLES

Late 1800 – Early 1900
- Golden period for the EVs
- Lead-acid powered Vehicles

By 1920
- Market dominated by ICE vehicles
- Long Range & High horsepower

2017 Onwards: EV30@30
- Environmental Concerns
- Renewed Interest In EVs

➢ Reason for EV to ICE Transition
- Heavy weight of batteries
- Short trip range
- Long charging time
- Poor battery life

ICE to EV Transition

Caution
Work in progress
ELECTRIC BUSES AROUND THE WORLD
How does it work?
## WHY ELECTRIC BUSES?

<table>
<thead>
<tr>
<th></th>
<th>Environmental Impacts</th>
<th>Operation &amp; Maintenance</th>
<th>Capital Investments and O&amp;M Expenses</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tail-pipe emissions</td>
<td>GHG emissions</td>
<td>Passengers comfort</td>
</tr>
<tr>
<td><strong>Diesel</strong></td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Noise generation</td>
<td>Technological maturity</td>
<td>Autonomy</td>
</tr>
<tr>
<td><strong>Hybrid</strong></td>
<td>-</td>
<td>-</td>
<td>++</td>
</tr>
<tr>
<td></td>
<td>Impact on depot design</td>
<td>Maintenance activity</td>
<td>Vehicle cost</td>
</tr>
<tr>
<td><strong>CNG</strong></td>
<td>-</td>
<td>-</td>
<td>++</td>
</tr>
<tr>
<td></td>
<td>Vehicle maintenance cost (Europe)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>H$_2$ Fuel cell</strong></td>
<td>+++</td>
<td>+</td>
<td>+++</td>
</tr>
<tr>
<td></td>
<td>Vehicle maintenance cost (India)</td>
<td>-</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Electric</strong></td>
<td>+++</td>
<td>+</td>
<td>+++</td>
</tr>
</tbody>
</table>
PERFORMANCE: EV VERSUS ICE VEHICLE

- Efficiency of EV is 5 to 6 times higher than that of ICE (Internal Combustion Engine) vehicles
- Gasoline is 100 times more energy dense than a battery

Stored Energy in Gasoline ~ 48 MJ/kg

Efficiency < 20 %

Stored Energy in Battery ~ 0.4 MJ/kg

Efficiency > 80 %

**BATTERY: COMPLEX FUEL TANK**

**Gasoline Powertrain**
- More Complex
- > 20,000 moving parts
- High Maintenance Cost

**Electric Powertrain**
- Less Complex
- < 20 moving parts
- Low Maintenance Cost

http://www.circuitstoday.com/working-of-electric-cars: Images from Web
BUS TECHNOLOGY

- Range & Routes
- Operational Schedule
- Energy Demand & Supply
- Energy Access
POWER TRAIN DESIGN
Major Components of Power Train
1. Battery Pack
2. Battery Management System
3. Traction Motor
4. Motor Controller
5. HV Power Distribution Unit
6. LV Power Distribution Unit
7. DC-DC Convertor
8. Vehicle Control Unit
9. Pneumatic System
10. Hydraulic System
11. Cooling System
12. Bus Aux unit
   - Compressor motor -> Compressor
   - Steering motor -> Steering
13. Lighting & Horn
POWER TRAIN COMPONENTS

- Motor
- Battery pack
- BMS
- Drive Train
- Vehicle Control system
- Data Acquisition system
- AUX unit
- Vehicle Control system
- Data Acquisition system
- AUX unit
EV motor drive is expected to be capable of offering a high torque at low speed for starting and acceleration,
And a high power at high speed for cruising.
At the same time as wide as possible speed range, under constant power, is desired.
BATTERIES USED IN EVS

- Pb-Acid
  - + Cost
  - + Recycling
  - - Energy Density
  - - Environment
  - - Weight

- NiCd
  - + Temperature
  - + Lifetime
  - - Environment
  - - Weight

- NiMH
  - + Power Density
  - + Cost
  - - Self discharge
  - - Cost

- Li-ion
  - + Energy Density
  - + Power Density
  - - Cost

- Li-air
  - Future Technology
  - (Under Development)

1859 onwards

Current
2019

Future
?
UNDERSTANDING PERFORMANCE INDICATORS

Environmental impact → Battery material and recycling potential

- Pb-acid / Ni-Cd / NiMH / LIB

Specific Energy (Wh/kg) – Range & Weight
Energy Density (Wh/l) – Range & Size
(Total amount of energy an energy storage device holds)

Specific Discharge Power (W/kg) – Acceleration & Weight
Discharge Power Density (W/l) – Acceleration & Size
(Speed at which the power can be discharged)

Safety
Cost
Battery Life
INSIDE LIB BATTERY

- **MONO-CELL**
  - BASIC CELL CHEMISTRY
  - BASIC VOLTAGE LEVEL

- **CELL**
  - STACK OF (e.g., 20) MONO-CELLS CONNECTED IN PARALLEL

- **MODULE**
  - MANY CELLS IN SERIES

- **BATTERY PACK**
  - SEVERAL MODULES OR MANY CELLS
  - VOLTAGE: 400 V

- **BATTERY SYSTEM**
  - SEVERAL BATTERY PACKS IN PARALLEL
  - ENERGY: >15 KWH

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WHY LIB FOR EVS?

Key Performance Requirements: High Energy Density, Long Cycle Life, Light Weight, Small Size

https://www.sciencedirect.com/science/article/pii/S1369702114000741; Others from Web
UNDERSTANDING LIB

GIF: https://gifer.com/en/LCEZ; Other images from Web
TYPES OF CELLS

Different form factors for Li-ion cells

Cylindrical cells

Prismatic cells

Pouch cells
LIB VARIANTS

• Three Chemistries for Buses- LFP, LTO & NMC

Balancing key performance parameters involves managing many trade-offs.
LIB: EFFECT OF TEMPERATURE

Desired Operating Temperature

- Limiting power to reduced T increase and degradation

Power Limits

- Sluggish Electrochemistry
- Rated Power
- Degradation

Dictates power capability through cold cranking

Dictates the size depending on the power and energy fade rate

15°C 35°C

Temp.

Battery Life

https://www.sciencedirect.com/science/article/pii/S1364032116301435
LIB: CHARGE RATE

C-rate: Rate at which battery is charged / discharged

SOC: State of Charge (SoC) describes how full a battery is

LIB: CHARGE RATE

DoD: Depth of Discharge (DoD) measures how much of stored energy is used at each cycle.
LIB: EFFECT CHARGE RATE & DOD

Cycle Life vs. Depth of Discharge (DOD)
Discharge 0.5 C / Charge 0.5C @ 25°C (77°F)

Remaining Capacity

0 2000 4000 6000 8000 10000 12000 14000

50% 55% 60% 65% 70% 75% 80% 85% 90% 95% 100%

50% DOD
80% DOD
100% DOD

https://batteryuniversity.com/learn/article/ultra_fast_chargers
https://modernsurvivalblog.com/alternative-energy/lithium-iron-phosphate-battery-cycles/
https://solarbuildermag.com/energy-storage/know-your-battery-specs-nameplate-capacity-10-kwh-vs-usable-capacity-/-kwh/
LIB: STATE OF HEALTH

SOH Indicates
- Performance of the battery
- Useful lifetime of the battery consumed

Any Arbitrary parameter defined by the Battery Management System
- Internal resistance / impedance / conductance
- Capacity
- Voltage
- Self-discharge
- Ability to accept a charge
- Number of charge–discharge cycles
- Age of the battery
- Temperature of battery during its previous uses
- Total energy charged and discharged

SOH does not correspond to one physical parameter but a combination!
LIB SAFETY: THERMAL RUNAWAY

Battery Management System (BMS) – To monitor and protect Li-ion battery during operation

https://advances.sciencemag.org/content/4/6/eaas9820.full;
## BATTERY PERFORMANCE VS RANGE

<table>
<thead>
<tr>
<th>Reduction in Range</th>
<th>Factor to be used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maintain 80% depth of discharge</td>
<td>0.8</td>
</tr>
<tr>
<td>100% passenger loading</td>
<td>0.85</td>
</tr>
<tr>
<td>AC Bus</td>
<td>0.92</td>
</tr>
</tbody>
</table>

The table shows the reduction in range for different factors affecting battery performance, along with the factor to use to maintain specific discharge levels or loading conditions.
DC SERIES MOTOR

• Motor is capable of producing high initial torque.

• The easy speed control and sudden load increase bearing capacity make these motors a good choice.

• But the high maintenance due to the brushes and commutators is a major drawback.
BRUSHLESS DC MOTOR (BLDC)

• High starting torque, high efficiency and low maintenance
• Used as Hub motors or belt driven
• Permanent magnets are used
PERMANENT MAGNET SYNCHRONOUS MOTOR

- Similar in construction to the BLDCs.
- But the major difference is in the back emf.
- PMSM has a sinusoidal back emf whereas BLDC has trapezoidal one.
- They have a high power rating and can be used in high-performance applications such as buses.
THREE PHASE INDUCTION MOTOR

- Induction motors don’t have a high starting torque.
- It is cheap as compared to the other available options.
- Very high efficiency and can withstand rugged environmental conditions.
- Tesla Model S uses this type of motor
**Opportunity charging**
- Recharging is enough for a one-way trip or less
- Recharging at bus stops and/or at bus terminals
- Little impact on bus operation

**Depot charging**
- Recharging is enough for several hours / plural round-trips
- Recharging overnight (usually)
- May have some impact on bus operation (autonomy)

**Mixed charging**
- Recharging at bus terminals during operation hours and at bus depots (usually at night) for full battery charge
- 2 battery technologies may be required (adapted recharge performance)
- Little impact on bus operation
<table>
<thead>
<tr>
<th>Depot Charging Only/Slow Charging</th>
<th>Depot Charging + Opportunity Charging</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lesser cost of charging infrastructure</td>
<td>Need additional charging infrastructure. Cost may go up.</td>
</tr>
<tr>
<td>May need extra fleet to cover along high demand corridors</td>
<td>Adherence to service schedules with lesser fleet size</td>
</tr>
<tr>
<td>High upfront cost due to large battery</td>
<td>Lower battery size can be used resulting in lower bus cost</td>
</tr>
</tbody>
</table>
HARGERS
TYPES OF CHARGERS

- Slow charging with a charging power of less than 50 kW (20 – 50 kW), and
- Fast charging with a charging power of 50-150 kW
- Ultra Fast Charging with a charging power >150 kW
CHARGING STANDARDS

• The Japanese CHAdeMO standard,

• The European Combined Charging Standard (CCS), which is also applied in North America, and

• The Chinese GB/T standard or protocol.
CHARGING STRATEGIES

Bus Schedule

Option 1: Fast
Option 2: Slow Charging

Schedule 1  Schedule 2
CITY BUS ELECTRIFICATION

Operational characteristics
- Bus routes topography
- Urban density
- Bus routes length and depot location

Direct and indirect costs
- Capital investment (buses and electric infrastructure)
- Operational expenses (electricity and recharging activities)
- Maintenance expenses (new activities and spare parts)

Recharge strategy
- “Fast” / Opportunity charging
- “Slow” / Depot charging
- Impact on deadhead and bus fleet

Battery autonomy
- Diesel / GNV = 250 to 350 km
- Electric battery = 30 to 240 km
- Battery lifespan
APPROACH FOR DEPLOYING E-BUSES

Route Selection (Range Estimation) ➔ Running Schedules ➔ Depot Locations ➔ Charging Strategies ➔ GPS Data (speed, stops, elevation) ➔ Battery Data (Energy Consumption, SoC) ➔ Monitoring & Evaluation
ROUTE SELECTION CRITERIA

- Ridership
- Daily Kms
- Replacement Ratio
- TCO
REPLACEMENT RATIO

This ratio is calculated as the ratio of the daily total kms travelled by a bus along specific route to the available or calculated range taking into consideration the depth of discharge, use of AC, passenger loading and battery degradation over time.
TOTAL COST OF OWNERSHIP

• Total Cost of Ownership- TCO is the Present Value of capital cost plus the Present Value of operating costs.

• Capital costs include that of E-bus and charging infrastructure

• Operational costs are the major cost components that make up the input.

• TCO provides an understanding of the various components that affect the overall economic performance of an E-bus over its lifetime.

• TCO is the key information that bus operators would need to know, since they will procure the E-buses.
GRACIAS

Thank you in different languages:
- SPANISH: GRACIAS
- PORTUGUESE: OBRIGADO
- RUSSIAN: SPASIBO
- ITALIAN: GRAZIE
- GERMAN: DANKE
- FRENCH: MERCI
- HEBREW: HASHAMAR
- JAPANESE: ARIGATO
- HINDI: TERIMA KASIH
- TYPICAL: TACK
- CZECH: DAW-DYEH
- POLISH: GRAZIES
- GERMAN: SPASIBO