PERFORMANCE OF ELECTRIC VEHICLES

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References

- Le véhicule électrique. Educauto. www.educauto.org
Performances of Electric Vehicles

- Vehicle driving performances are assessed by
  - Acceleration time
  - Maximum speed
  - Gradeability

- In EV drive train design: motor power rating and transmission parameters are selected to meet the performance specifications

- They depend mostly on speed-torque characteristics of the traction motor
Traction motor characteristics

- At low speed: constant torque
  - Voltage supply increases with rotation speed through electronic converter while flux is kept constant

- At high speed: constant power
  - Motor voltage is kept constant while flux is weakened, reduced hyperbolically with the rotation speed

- **Base speed**: transition speed from constant torque to constant power regime
Traction motor characteristics

- Speed ratio $x = \text{ratio between maximum rotation speed to base speed}$
  - $X \sim 2$ Permanent Magnet motors
  - $X \sim 4$ Induction motors
  - $X \sim 6$ Switched Reluctance motors

- For a given power, a long constant power region (large $x$) gives rise to an important constant torque, and so high vehicle acceleration and gradeability. Thus the transmission can be simplified.
Tractive efforts and transmission requirement

- Remind traction effort and vehicle speed
  
  $$ F_t = \frac{C_m i \eta_t}{R_e} $$
  
  $$ v = \frac{\omega_m R}{i} $$

- The use of multi-gear or single gear transmission depends on the motor speed-torque characteristics.
  - For a given rated power, a long constant power region makes possible to use a single gear transmission, because of high tractive efforts at low speeds.
  - For long constant torque and a given rated power, the available maximum torque is not sufficient so that a multi gear is generally preferred.
Tractive efforts and transmission requirement

- For a low \( x (x=2) \) motor, tractive effort is not large enough and 3-gear transmission is chosen.
- For intermediate \( x=4 \), a two gear transmission is preferred.
- For a large \( x=6 \), a single gear transmission is chosen.
- The 3 designs have the same Tractive Force / speed profiles, and so the same acceleration and gradeability performances.
Tractive efforts and transmission requirement

Motor speed ratio: $x = 4$

Single-gear transmission
Motor speed ratio: $x = 6$
Max speed can be evaluated by calculating the intersection between the tractive force curve and the resistance curve or alternatively the tractive power (constant) and the resistance forces power.

\[ \eta P_{m}^{\text{max}} = AV_{\text{max}} + BV_{\text{max}}^3 \]

Sometimes the intersection does not exist because it is over the maximum rotation speed of the motor

\[ V_{\text{max}} = \frac{\pi N_{m}^{\text{max}} R_e}{30i} \]
Gradeability of EV

- Gradeability is ruled by the net tractive force available

\[ F_{t}^{\text{net}} = F_t - F_{rlt} - F_{aero} = F_t - mgf \cos \vartheta - 0.5 \rho SC_x V^2 \]

- The maximum grade that can be overcome at a given speed is:

\[ \sin \vartheta = \frac{F_t - F_{rlt} - F_{aero}}{mg} = \frac{F_{t}^{\text{net}}}{mg} \]

- One gets:

\[ \sin \vartheta = \frac{d - f \sqrt{1 - d^2 + f^2}}{1 + f^2} \]

\[ d = \frac{(F_t - F_{aero})}{mg} \]
**EV acceleration**

- Acceleration can be evaluated by the time to accelerate from a given low speed (often zero) to a given high speed (e.g. 100 km/h).
- Acceleration performance is often more important for drivers than max speed and gradeability.
- Acceleration performance dictates the power rating of the motor.
EV acceleration

- Acceleration time can be calculated by the integral

\[
t_a = \int_0^{V_b} \frac{\gamma m}{P_t/V - mgf - 0.5 \rho C_x SV^2} \, dV + \int_{V_b}^{V_f} \frac{\gamma m}{P_t/V - mgf - 0.5 \rho C_x SV^2} \, dV
\]

- Approximation solution: neglect the rolling and the drag resistances

\[
t_a = \frac{\gamma m}{2P_t} (V_f^2 + V_b^2)
\]
EV acceleration

- Sizing of rated power of electric motor

\[
P_t = \frac{\gamma m}{2t_a} (V_f^2 + V_b^2)
\]

- However to determine more accurately the rated power, one needs to determine the power consumption of the resistance forces

\[
\bar{P}_{aver} = \frac{1}{t_a} \int_0^{t_a} mgfV + 0,5 \rho SC_x V^3 dt
\]
EV acceleration

- As the power is supposed to be constant in some part of the acceleration, one gets the cinematic relation

\[ V = V_f \sqrt{\frac{t}{t_a}} \]

- Inserting into the integral, it yields

\[ \bar{P}_{\text{aver}} = \frac{2}{3} mgf V_f + \frac{1}{5} \rho SC_x V_f^3 \]

- It comes the estimated power of the motor

\[ P_t = \frac{\gamma m}{2t_a} (V_f^2 + V_b^2) + \frac{2}{3} mgf V_f + \frac{1}{5} \rho SC_x V_f^3 \]
The result shows that for a given acceleration performance, low vehicle base speeds will result in small motor power rating.

However the power rating decline rate to the vehicle base speed reduction is not identical:

\[
\frac{dP_t}{dV_b} = \frac{\gamma m}{t_a} V_b
\]
EV acceleration

$P_t = 63 \text{ kW}, x = 4$
$M_v = 1200 \text{ kg}, f_r = 0.01$
$C_D = 0.3, A_f = 2.0 \text{ m}^2$
Acceleration capacity and impedance adaptation

- 1D system with one electric motor connected to the mechanical load via a gear box or reduction ration $r$
  - $M$ mass of load
  - $J$ inertia of electric motor
  - $r = \frac{Re}{i}$
  - $a$ acceleration of load

- Dynamic equilibrium
  \[ T = \left( \frac{J}{r} + m r \right) a \]

- Acceleration
  \[ a = \frac{T r}{J + m r^2} \]
Acceleration capacity and impedance adaptation

- Derivative of acceleration with respect to gear ratio

\[ \frac{da}{dr} = \frac{T}{J + Mr^2} - \frac{2r^2 TM}{(J + Mr^2)^2} = 0 \]

- Optimal gear ratio

\[ r_{opt} = \sqrt{\frac{J}{m}} \]

- Optimal acceleration power

\[ a_{max} = \frac{1}{2} \frac{T}{\sqrt{mJ}} = \frac{1}{2} \frac{T}{r_{opt} m} \]

- Conclusion: this is the maximum acceleration that can be given to the load by a motor with maximum torque T
EV accelerations in normal operation

- Driving cycle $V(t)$ is given
- Evaluate the acceleration required: differencing the velocity profile in function of the time,
  \[
  \frac{dV}{dt} \approx \frac{V(t_{k+1}) - V(t_k)}{t_{k+1} - t_k}
  \]
- Tractive force is given by the net force necessary to follow the driving cycle
  \[
  F_t = mgf \cos \vartheta + \frac{1}{2} \rho C_D SV^2 + m\gamma \frac{dV}{dt}
  \]
EV accelerations in normal operation

(a) FTP 75 urban

(b) US 06
EV accelerations in normal operation
EV accelerations in normal operation
EV accelerations in normal operation
EV energy consumption

- In transportation the unit of energy is usually the kWh (kiloWatt hour) (preferred to Joules Joule kJ)
  - ICE with liquid fuels: L/100 km or mpg
  - Gaseous fuel (CH4, H2): kg/100 km

- Advantage: size of batteries given in kWh at battery ports so that the driving range can be calculated immediately

- Energy consumption is the time integration of the power output and input at the battery terminal.
Energy power output
- Equal to the resistance power and the power losses in the transmission and motor drive including the power electronic loses

\[ P_{bat}^{in} = \frac{V}{\eta_t \eta_m} (mgf + mg \sin \vartheta + \frac{1}{2} \rho S C_D V^2 + m \gamma \frac{dV}{dt}) \]
- The non traction loads are not included (auxiliary loads) while they can be significantly important and they should be added to the traction load.
EV energy consumption

- The efficiency of the traction motor varies with the operating points on the speed-torque (speed-power) plane.

- Good design: large overlap between maximum efficiency region and the region of visited by the greatest operation points.
EV energy consumption

- The regenerative braking power at battery can be evaluated as

\[
P_{bat}^{out} = \alpha \frac{V}{\eta_t \eta_m} (mgf + mg \sin \theta + \frac{1}{2} \rho S C_D V^2 + m \gamma \frac{dV}{dt})
\]

- In which
  - Road slope sin \( \theta < 0 \) and/or \( \frac{dV}{dt} < 0 \)
  - \( 0 < \alpha < 1 \) is the fraction of energy recovered during braking
    - The braking factor \( \alpha \) is a function of the applied braking strength and the design and control of braking system
  - Typical value of energy recovery fraction \( \alpha = 0.3 \)
EV energy consumption

- The **net energy consumption** from batteries is:

\[ \hat{E}_{n_{out}} = \int_{\text{traction}} P_{bat}^{out} dt - \int_{\text{braking}} P_{bat}^{in} dt \]

- When the net battery energy consumption reaches the total energy in the batteries, measured at terminal, the batteries are empty and need to be charged.
- The traveling distance between two charges is called the **effective travel range**.
- It is dependent on the battery capacity, the road resistance power, the driving cycle, the effectiveness of regenerative braking, the efficiency of the car and its powertrain.