E-PAWNEE

A good idea or not?

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Some reasons to suspect it might...

- Fossil fuels will be frowned upon and are expensive.
- Biofuels have ethical problems, don’t exist yet as AVGAS, and will be more expensive when/if they do.
- E-fuel does not exist yet, much less as AVGAS and will be expensive when/if they do.
- Chemical fuel requires a cistern that needs permits, inspections and maintenance.
- ICE Pawnees are noisy and the engine has many moving parts.
- Pawnee airframes are relatively light, sturdy, cheap and can carry a fair weight.
- Lots of checked out tow pilots.

Some reasons to suspect it might not...

- Drag
- Weight
- Cost; draggy plane → large motor+battery
- Rules: certified planes requires STC, experimental easier

Parameters

- Airframe: mass, drag coefficient, span, span efficiency
- Motor: characteristics, kW/kg, converter kW /kg and efficiency, cooling drag, regeneration
- Battery: kWh/kg, C in, C out
- Propeller diameter, RPM, characteristics (noise), wake velocity
- Charging: grid connection power, fee/kW, static battery capacity, C out, solar panels power
- Cost plane: motor €/kW, converter €/kW, battery €/kWh, installation materials & labour
- Cost charging: grid connection €/kW, battery €/kWh, € charger
- Cost operations: €/kWh, battery # of cycles, maintenance, repairs, insurance

Fossil parameters

- Performance: excess power, liter/kWh
- Cost fuelling: tank permit, inspection, maintenance
- Cost operations: fuel €/liter, oil, maintenance, repairs, engine replacement

John von Neumann famously said:
With four parameters I can fit an elephant, and with five I can make him wiggle his trunk .

Airframe

In[1]:=
```
slider[expr_, {{var_, init_}, min_, max_}] :=
 Manipulate[expr, {{var, init}, min, max}, Initialization :> (expr = init;),
  LocalizeVariables -> False, BaseStyle → {FontColor -> GrayLevel[0]},
  ControlPlacement -> Left, DefaultLabelStyle -> {FontSize -> 30}];
"_"
```

Out[1]= _

In[2]:=
```
g = 9.80665;
ρair = 1.225;
mtotIXI = 1000;
mEmpty = 700;
mO540 = 210;
mTank = 15;
mOil = 8;
mStartBatt = 10;
mFuel = 147 × 0.7;
mPilot = 110;
mICE = mEmpty + mFuel + mPilot;
mHullIXI = mEmpty - mO540 - mTank - mOil - mStartBatt;
spanIXI = 11.02;
eSpanIXI = 0.8;
dragAreaIXI = 1.45;
towSpeed = 120;
ldMax = 7;
```

In[•]:= mICE

Out[•]= 912.9

In[19]:=
```
Clear[mtot,mHull,eSpan,span,uInf,dragArea];
CreatePalette[TableForm[{slider[mtot, {{mtot,mtotIXI},900,1100}],
slider[mHull, {{mHull,mHullIXI},300,800}],
slider[eSpan, {{eSpan,eSpanIXI},0.5,1}],
slider[span, {{span,spanIXI},8,30}],
slider[dragArea, {{dragArea,dragAreaIXI},0.2,2}],
slider[uInf, {{uInf,towSpeed},1,140}]}],WindowTitle->"Airframe"];
"Airframe palette"
```

Out[21]= Airframe palette

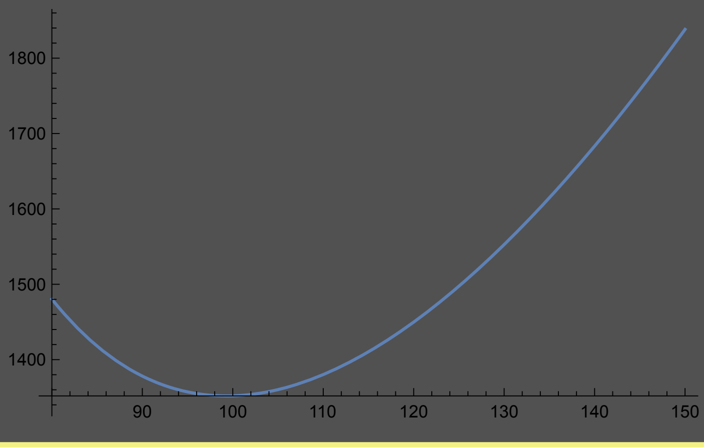
In[22]:=
```
uinf = Dynamic[uInf / 3.6];
mPropulsion = Dynamic[mtot - mHull]
```
Out[23]= 543

In[24]:=
```
d0[ρ_, v_, a0_] := ρ/2 v^2 a0
```

In[25]:=
```
di[ρ_, m_, v_, b_, e_] := (m g)^2 / (ρ/2 v^2 Pi b^2 e)
```

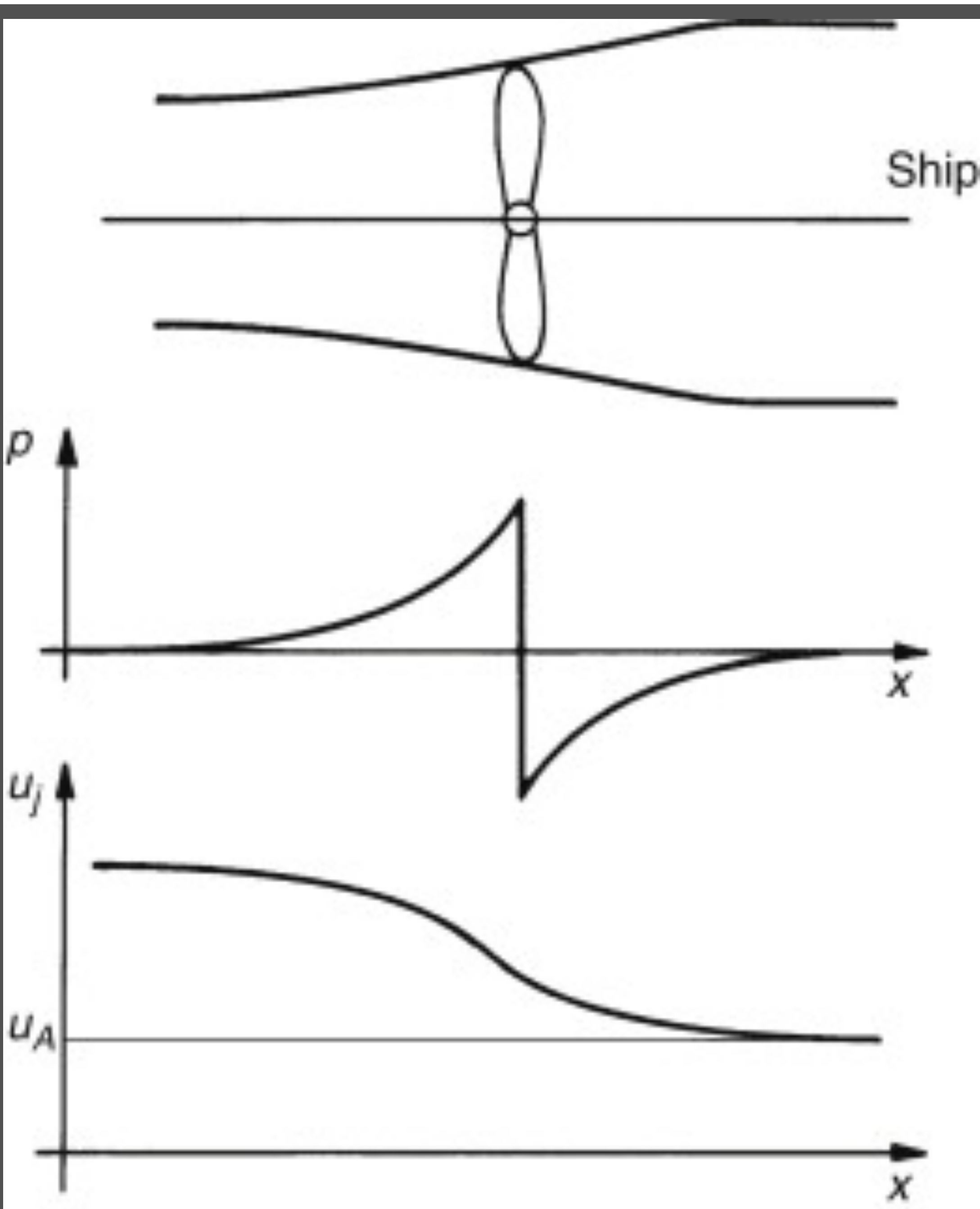
In[26]:=
```
drag[ρ_, m_, v_, b_, e_, a0_] := d0[ρ, v, a0] + di[ρ, m, v, b, e]
```

In[27]:=
```
glideRatio = Dynamic[mtot g / drag[ρair, mtot, uinf[[1]], span, eSpan, 1.45]]
```
Out[27]= 6.76415

In[28]:=
```
Dynamic[Plot[drag[ρair, mtot, v / 3.6, span, eSpan, dragArea], {v, 80, 150}]]
```
Out[28]=


Propulsion

Momentum theory for the propeller, i.e an actuator disc.



In[29]:=
```
pShaftIXI = 175 000;
dPropIXI = 1.8;
propEtaRotIXI = 0.82;
sfc = 0.42 / 0.74569987 × 0.7;
sfcDescent = sfc 0.1;
descentRate = 5;
```

Out[37]= Propulsion palette

In[38]:=
```
pAirProp = Dynamic[pShaft propEtaRot];
aDisc = Dynamic[(dProp / 2)^2 Pi];
sol = Solve[2 a (1 + a)^2 u^3 ρ (0.5 d)^2 Pi == p, {a}];
aInd = Dynamic[
    (sol //. {d -> dProp, p -> pAirProp[[1]], u -> uinf[[1]], ρ -> ρair} // N)[[
     3, 1, 2]]] ;
vWake = Dynamic[(1 + 2 aInd[[1]]) uinf[[1]]];
thrust = Dynamic[ρair / 2 aDisc[[1]] (vWake[[1]]^2 - uinf[[1]]^2)];
pExcess = Dynamic[
    uinf[[1]] × (thrust[[1]] - drag[ρair, mtot, uinf[[1]], 11.02, 0.8, 1.45])];
```

Solve: Solve was unable to solve the system with inexact coefficients. The answer was obtained by solving a corresponding exact system and numericizing the result.

Out[ ]=

Prop disc area	2.54469
Disc induced velocity	0.34403
Wake velocity	56.2687
Thrust	3203.05
Drag	1438.51
Excess power	58 441.8

Electric propulsion

Out[47]= Electric propulsion palette

In[48]:=
```
emotorPower = Dynamic[pShaft / etaEmotor];
batteryPower = Dynamic[pShaft / ( etaEmotor etaInverter etaBattery )];
emotorMass = Dynamic[emotorPower[[1]] / emotorPowerDensity];
inverterMass =
  Dynamic[pShaft / etaEmotor / etaInverter / inverterPowerDensity];
batteryPackMass = Dynamic[mtot - mPilot - mHull - emotorMass[[1]] -
     inverterMass[[1]] - eCoolingMass - eOtherMass];
batteryEnergy = Dynamic[batteryPackMass[[1]] / batteryPackFactor
     batteryEnergyDensity];
batteryMaxPower = Dynamic[batteryEnergy[[1]] batteryDischargeRate];
```

Out[55]=

Batttery pack mass	385.238
Battery energy	74 084.2
Battery max power	222 253.

Operations

Out[58]= Operations palette

In[59]:=
```
gliderDrag = Dynamic[gliderMass g / gliderLD];
pGlider = Dynamic[uinf[[1]] × gliderDrag[[1]]];
pExcessTow = Dynamic[pExcess[[1]] - pGlider[[1]]];
climbRateTow = Dynamic[pExcessTow[[1]] / (g (mtot + gliderMass))];
climbTime = Dynamic[towHeight / climbRateTow[[1]]];
descentTime = Dynamic[towHeight / descentRate];
towTime = Dynamic[climbTime[[1]] + descentTime[[1]] + 60];
fuelPerTow = Dynamic[(climbTime[[1]] * sfc + descentTime[[1]] * sfcDescent)
      pShaft / 1000 / 3600 / 0.7 + 1] ;
whPerTow = Dynamic[climbTime[[1]] * batteryPower[[1]] / 3600] ;
reserveCharge = Dynamic[reserveTime mtot g / ldMax
     110 / 3.6 / 0.7 / etaBattery / etaEmotor / etaInverter / 3600];
usefulCharge = Dynamic[batteryEnergy[[1]] - reserveCharge[[1]]];
nTow = Dynamic[usefulCharge[[1]] / whPerTow[[1]]];
rechargeTimeOneTow =
   Dynamic[whPerTow[[1]] / (batteryEnergy[[1]] batteryChargeRate) 3600];
sustainedCadence = Dynamic[
    3600 / (climbTime[[1]] + descentTime[[1]] + 300 + rechargeTimeOneTow[[1]])];
```

Out[73]=

Glider power	6129.16
Tow excess power	52 312.6
Tow climb rate	3.334
Tow climb time [min]	3.4993
Tow time [min]	6.83263
Fuel per tow	7.13179
kWh per tow	11 300.5
Reserve charge	11 284.8
Useful charge	62 799.4
Tows per useful charge	5.55721
Recharge time 1 tow	183.044
Max tows/h	4.32172

Economy

Out[76]= Economy palette

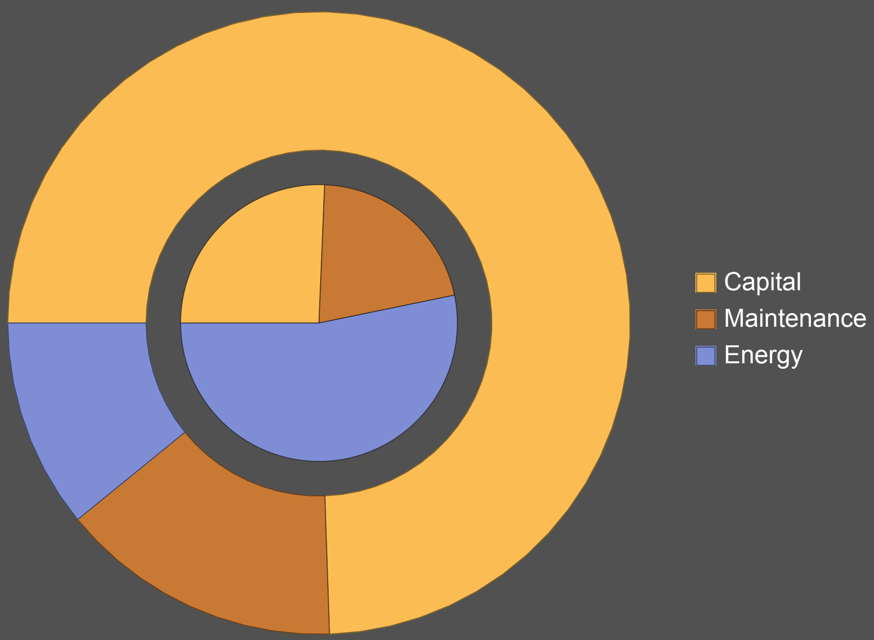
In[77]:=

```
batteryCost =
  Dynamic[batteryEnergy[[1]] batteryCostKWH batteryPackFactor / 1000];
emotorCost = Dynamic[emotorPower[[1]] emotorCostKWH / 1000];
inverterCost = Dynamic[emotorPower[[1]] inverterCostKWH / 1000];
eCoolerCost = 1000;
O540CoreValue = 12 000;
ePropulsionCost =
  Dynamic[batteryCost[[1]] + emotorCost[[1]] + inverterCost[[1]] + eCoolerCost];
icePlaneValue = Dynamic[hullValue + O540CoreValue + O540CostTBO];
ePlaneValue = Dynamic[(hullValue + ePropulsionCost[[1]]) eDevCostFactor];
hoursPerYear = Dynamic[towTime[[1]] towsPerYear / 3600];
annualsPerYear = Dynamic[Max[1, hoursPerYear[[1]] / (100)]];
h50PerYear = Dynamic[Max[0, (hoursPerYear[[1]] - 50) / 100]];
iceCapitalCost = Dynamic[icePlaneValue[[1]] (insuranceRate + interestRate)];
iceMaintenanceCost = Dynamic[
   annualsPerYear[[1]] (10 O540CostOil + O540CostAnnual + hullCostAnnual) +
    h50PerYear [[1]] (10 O540CostOil) + O540CostRepair];
iceTBOCostPerYear = Dynamic[O540CostTBO / hoursPerYear[[1]]];
iceEnergyCostPerTow = Dynamic[fuelPerTow[[1]] avgasCost];
iceCostPerYear =
  Dynamic[iceCapitalCost[[1]] + iceEnergyCostPerTow[[1]] towsPerYear +
    iceMaintenanceCost[[1]] + iceTBOCostPerYear[[1]]];
iceCostPerTow = Dynamic[iceCostPerYear[[1]] / towsPerYear];
eCapitalCost = Dynamic[ePlaneValue[[1]] (insuranceRate + interestRate)];
eMaintenanceCost = Dynamic[annualsPerYear[[1]]
     (O540CostAnnual + O540CostRepair) eMaintenaceRatio + hullCostAnnual];
eBatteryCyclesPerYear = Dynamic[batteryEnergy[[1]] / towTime[[1]] / 1000
    towsPerYear];
eBatteryCostPerYear = Dynamic[batteryCost[[1]] ×
    eBatteryCyclesPerYear[[1]] / batteryMaxCycles];
eEnergyCostPerTow = Dynamic[whPerTow[[1]] / 1000 kWhCost];
eCostPerYear =
  Dynamic[eCapitalCost[[1]] + eEnergyCostPerTow[[1]] towsPerYear +
    eMaintenanceCost[[1]] + eBatteryCostPerYear[[1]]];
eCostPerTow = Dynamic[eCostPerYear[[1]] / towsPerYear];
```

Out[101]=

Battery price	19 261.9
Electric motor price	20 052.1
Inverter price	10 937.5
Electric propulsion price	51 251.5
ICE plane value	77 000
Electric plane value	162 503.
Hours per year	79.714
Annuals/100h	1
50h per year	0.29714
ICE plane capital cost	3850.
ICE plane maintenace cost	3168.63
ICE TBO cost per year	439.07
ICE plane energy cost per tow	11.4109
ICE plane cost per year	15 445.3
ICE plane cost per tow	22.0647
Electric plane capital cost	8125.15
Electric plane maintenance cost	1600.
Battery cycles per year	126.498
Battery cost per year	2436.6
Electric plane energy cost per tow	1.69508
ELectric plane cost per year	13 348.3
Electric plane cost per tow	19.069

Out[•]=



Inner pie is ICE, outer is electric.

Conclusions

- Drag is expensive.
- Good financing and/or DIY is crucial.

- More activity brings cost per tow down, but likely harder with electric plane in high cadence situations.
- E-Pawnee not really a good idea with current battery energy density and price.