CARPET PLOT DATA FORMAT

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Analysis and interpretation of data is the crucial phase of the decision making process. The interplay between variables must be considered as to their relative significance upon the final result, and sometimes time-sensitive decisions must be made when actual events deviate from predicted information, such as Apollo 13. As the number of variables increases past say four, the traditional method of cross-plotting tends to breakdown, and digital/analog results cannot present a sharply defined method of analysis. A graphical system is suggested. I named it "carpet plot," (since it covers anything), in which an unlimited number of complicated relationships of variables can be evaluated.

Introduction

The presentation and analysis of data involving more than two variables has traditionally been accomplished by cross-plotting data and results. An engine test is typical of this scheme, in which rpm, dynamometer load and engine temperatures are varied.

Three graphs are required, none of which define the interlationship completely, as shown in Figures 1, 2, and 3, in that one of the variables is always missing. As more variables are brought into the picture, such as spark timing, compression ratio, octane number, etc., the proliferation of graphs necessary to present the data becomes excessive, possibly increasing exponentially.

An entirely different situation exists when a fixed result can be achieved by a multiple combination of several variables. Taking a simple case, the Fourier equation for one dimensional conductive heat flow,

$$q = -KA \frac{dt}{dx} \qquad (1)$$

shows that q can be adjusted to a predetermined value by an almost infinite combination of variables. For instance, if dt is doubled for a constant K and A, dx should be doubled. If K changes by a factor of 1.4, A by 0.8, dx by 0.6, then dt can change by a factor of 1.9 and still have the same numerical value of q.

This type of problem is entirely different than the engine test type. As the system becomes more complex, and the number of variables increase and commence to interact, the difficulty of analysis increases. The carpet plot represents a new method of data presentation to simplify analysis. There is theoretically no limit to the number of variables.
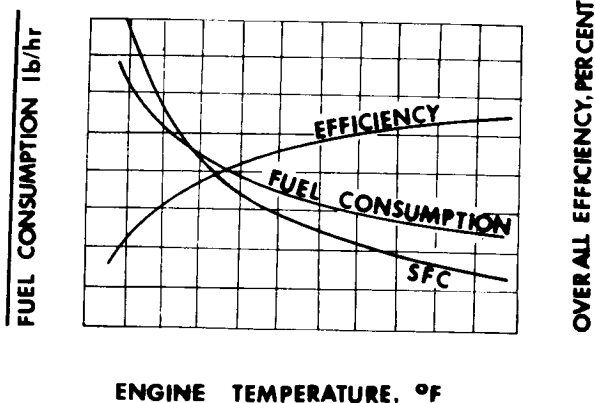

Figure 1. Plot shows the effect of dynamometer load variation on fuel consumption and other operating parameters of an internal-combustion engine
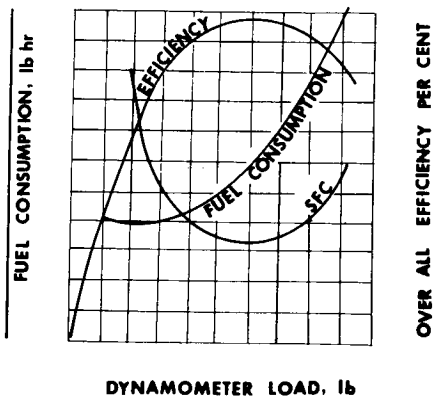

Figure 2. Plot shows the effect of engine temperature on fuel consumption and other operating parameters of an internal-combustion engine
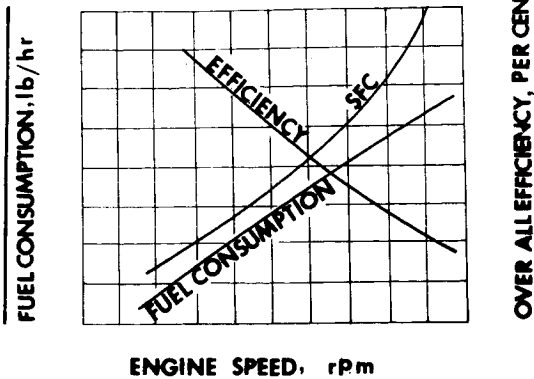
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FUEL CONSUMPTION, lb/hr

OVER ALL EFFICIENCY, PER CENT

EFFICIENCY SFC

FUEL CONSUMPTION

ENGINE SPEED, rPm

Figure 3. Plot shows the effect of engine speed
on fuel consumption and other operat-
ing parameters of an internal-
combustion engine.

Example of a Carpet Plot

A simple heat transfer problem was selected
which could be analyzed mathematically and verif-
ied by laboratory equipment. Figure 4 shows an
insulated cylinder filled with m lb. of water; its
average temperature, t, is measured by six thermo-
couples wired in parallel. A helical cooling coil
is placed in the tank, through which water flows
at a mass flow rate W, regulated by an outlet
valve and measured by a rotameter. A variable
power heater is installed inside the tank, whose
energy can be controlled by a rheostat and
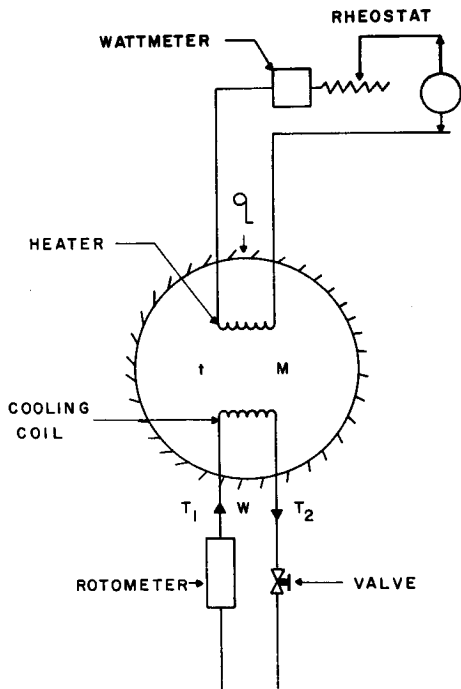measured with a wattmeter.

Figure 4. Schematic diagram of equipment used
in a transient heat transfer
experiment

With no heat application to the system, water is
passed at a constant rate through the cooling coil
until thermal equilibrium is reached in the tank.
At time zero, the heater is turned on, and the
problem is to predict the transient and steady-
state values of the tank water as a function of
time.

For a fixed value of W and M, various values of
q were selected and the tank temperature calculated
by conventional methods as a function of time, θ; a
typical parametric graph is shown in Figure 5, in
which the θ scale is constructed by conventional
methods.

Assuming that the tank temperature is of little
interest at low values of θ, Figure 6 modifies
Figure 5 by ignoring the low θ values, bringing the
θ values vertically into the graph, and erasing the
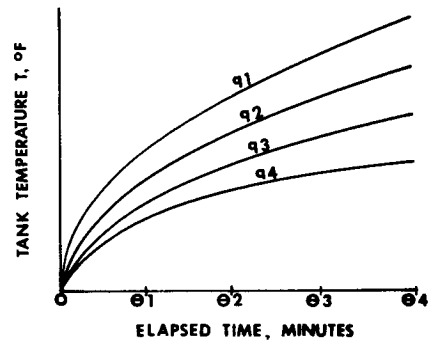"old" θ scale; each of the θ values are labeled.

Figure 5. Traditional time-temperature plots
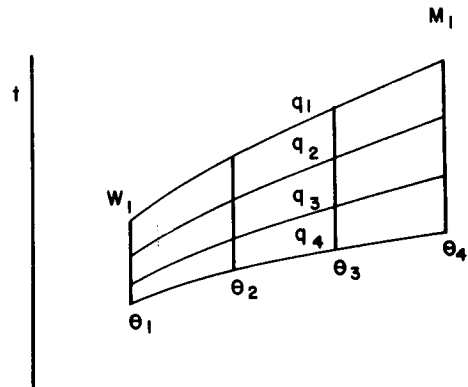with parametric heat loads

Figure 6. First step in a carpet plot technique

The graph, up to this time, has been for a
constant W_1 and M_1. The carpet plot proceeds in
Figure 7, in which for the same values of q and θ,
a different coolant flow rate W_2 is desired. This
effect is introduced by moving some convenient
physical distance (3 inches, 6 inches, etc.),
constructing a new time scale θ, on the traditional
basis and plotting tank temperature t, as a function
of the same $q_1 - q_4$, m_1, and a constant W_2, on the
"old" t scale. (The "new" W_2 plot will probably
not be in a horizontal line with the W_1 graph). A
significant feature of the carpet plot is that the

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result, t, for all the variables uses only one scale.

For the W_2 parametric graph, the same procedure is used as previously done; bring θ into the graph, ignore small values of θ, erase the θ scale, and label the vertical θ lines; this step is shown in Figure 8.

Attention is drawn to the fact that at say the left hand bottom corner of the W_1 plane of Figure 8, a point exists for a W_1, q_4, and θ_1 value, M being a constant. Likewise the left hand bottom corner of the W_2 plane has the same q_4 and θ_1, M at the same constant. Thus, q_4 and θ_1 values are common values, and any line connecting them will have the same q_4 and θ_1. Figure 9 expands this concept to account for more points.

The carpet plot takes on a 3-dimensional appearance; however, it is plotted on a flat sheet of paper and is not 3-D. It also differs from an X-Y-Z coordinate system, in that no axis is foreshortened. The stories of the box represent various q values, the ends represent various W's, and vertical slices are various values of θ.

Only two values of W are shown; in practice, at least more than three should be computed in order to establish the correct trends; the author uses four values of W as a minimum to assure that no inflections, etc., occur.

Assuming that the W_1 and W_2 planes correctly identify the tank temperature, recall that their physical separation (say 3 inches) was completely arbitrary. A plane half way between W_1 and W_2 would logically represent conditions of $W_{1\ 1/2}$; give your children the game of drawing in this interpolated plane, as shown in Figure 10, whose appearance is similar to the existing computed planes; its numerical accuracy is only a function of the artist's ability. In a similar fashion, moving 6 inches to the right of plane W_1 would logically represent a plane of W_3 conditions which can be drawn in by eye. If the interconnecting lines of common values between W_1 and W_2 are correct, and the performance of the system is assumed to be logical at higher values of W_2, then theoretically there is no limit to the extent of extrapolation and interpolation as shown in Figure 11.
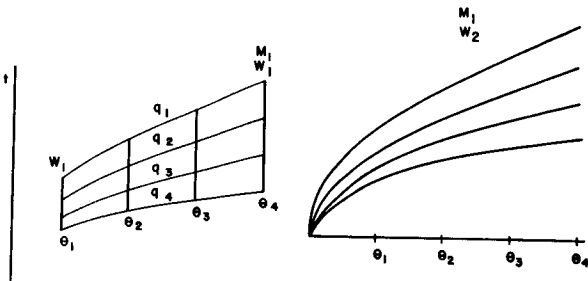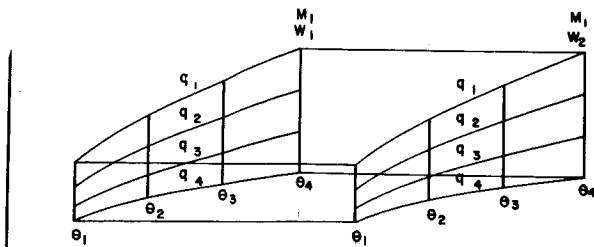

Figure 7. Extension of Fig. 6 for a different mass flow rate
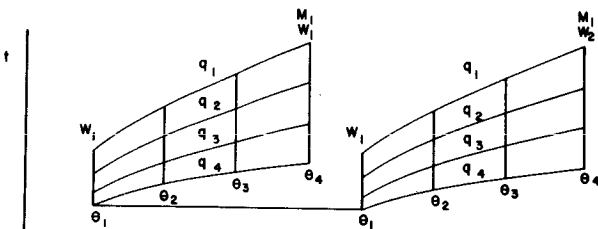
Figure 8. Common property representation for a fixed mass

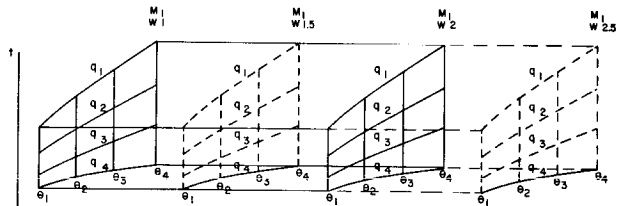Figure 9. Extension of Fig. 8

Figure 10. Technique of extrapolation and interpolation
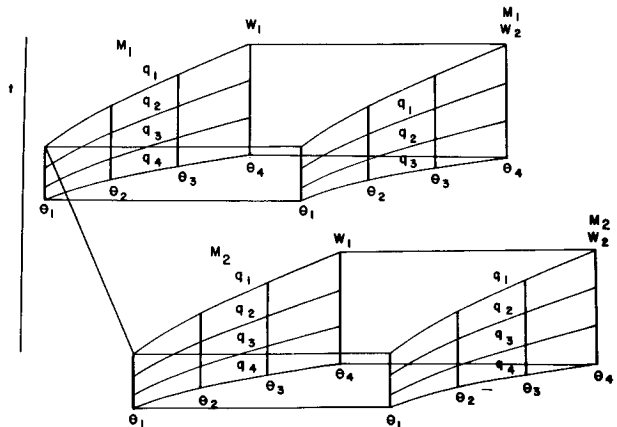

Figure 11. Introduction of a new variable into the carpet plot

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To this point, the carpet plot technique has held the mass of tank water, M_1, as a constant. Let us extend the previous concepts in order to change M_1 to M_2 for the same values of θ, q, and W. The vertical location of the new M_2 plane is fixed by the temperature scale, but the horizontal location is arbitrary, as was the selection of the W_2 plane location. Basically, the problem is only to select a separation distance which will not cause overlapping of the planes. By repeating the calculations, for the same q's, W's and θ's, using a new value of M_2, Figure 11 shows the results. Only one interconnecting line between M_1 and M_2 is shown for clarity to permit interpolation and extrapolation of the M values in a fashion similar to the W values. The first objectives, presentation of coherent data for more than two variables, and logical interpolation and extrapolation of data, have been established. The variables were changed in a nested DO loop and the results computed on a CDC 3600 machine.

The next phase of utilization of a carpet plot is shown in Figure 12, which quickly shows that a tank temperature T_x will result when the system is operated with heat rate $q = q_4$, $W = W_1$, $\theta = \theta_3$ at $M = M_1$. Note that temperature at x can also be reached at $W = W_2$, $\theta = \theta_1$, $q = q_2$, an entirely different set of operating conditions. The carpet plot shows an almost infinite number of combinations. More frequently is that an operating T_x is required, and what combinations of variables will permit this T_x condition? Entering the carpet plot at the T_x value, all possible combinations can be determined rapidly and easily.
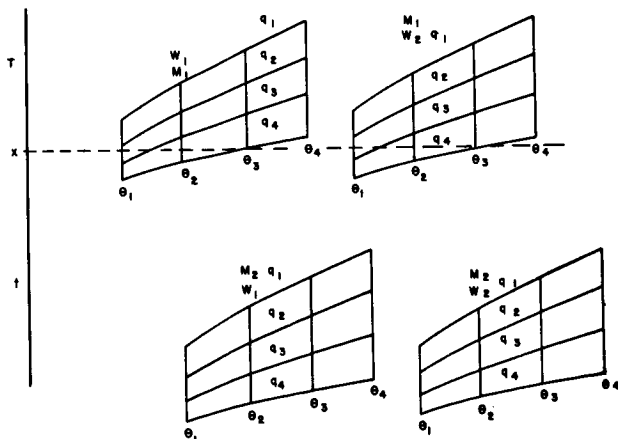
In addition to presenting every correct solution, the carpet plot will indicate every incorrect combination of variables. For instance, if temperature T_x is desired, it is perfectly obvious that M_2 cannot be used under conditions of any q, W and θ. In engineering work, the input to a data collecting or computing system is some desired performance which may change daily due to updating of information from other groups; the carpet plot permits a rapid analysis of operating conditions to achieve the result.

Another feature of the carpet plot permits an evaluation of the effect of the change in a variable upon the result. The differential equation method could be used, or the uncertainty method (1), but these techniques are extremely tedious as the number of variables increases; Figure 13 demonstrates this capability. Varying only one property, holding all others constant, the effect upon the result is shown schematically, in that dt_2 and dt_4 are about the same small magnitude, dt_1 is somewhat larger, and dt_3 far overshadows the others. The significance of this is immediately and clearly evident to a manager planning his work priorities, to define which variable should receive the major attention. In this case, it backs the previous invalid M_2 inoperative conditions for T_x, and shows that major design efforts for the system are necessary to prevent it from accidently shifting from M_1 to M_2.

Figure 12. Method of determining all possible solutions
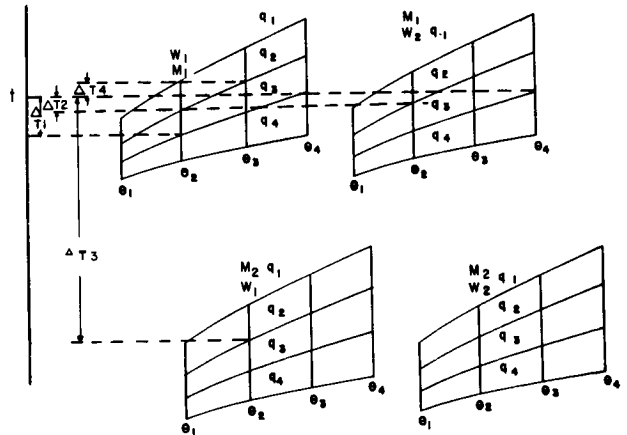

Figure 13. Relative effect upon a result with changes of a variable

Students at the University of Massachusetts proposed a detective game, in which they placed some water in the tank, then sealed it; the amount of water was not known by the writer; they set in values of power and flow rate. Access to the writer was permitted to the wattmeter, rotameter, and temperature recorder, and they posed the question: "Before the experiment ends, tell us how much water is in the tank." The appropriate heat loads and flow rates were rapidly sketched into the basic carpet plot values, and the interpolated tank water weight was established in minutes. The significance of this experiment is that the value of unmeasured and/or unknown quantities can be inferred by use of the carpet plot.

The utility of a carpet plot is unlimited. For instance, how much will the price of an automobile change as the number of coats of paint change, the color and weight of the dash padding, the quality of the spark plugs, the number of instruments, radiator size, etc. Which of the many variables is most significant?

This technique was applied to the analysis of variables associated with high performance insulation to be used on upcoming space programs such as nuclear stages in space. Only the thermal aspect was considered, but factors such as manufacturing, fabrication, cost, etc., could easily be brought into the picture. The George C. Marshall Space Flight Center has evaluated the performance of the Mars nuclear vehicle for the variables shown in Table I.

A part of this analysis is shown in Figure 14 to introduce the reader to the upcoming coordinate system. Considering only the variables of mission time, density, thickness, the weight penalty is presented in a traditional fashion; note that the remaining variables do not appear, and their effects are unknown; the information is incomplete.

Figure 15, with time scales varying, presents an almost complete version of a typical carpet plot, with a few of the variables omitted due to reproduction difficulties. Typical design parameters are immediately evident, such as no matter which of the assumed conductivities is used, large diameter tanks will have a lower weight penalty. Insulation thickness is more critical than density, and design effort in this area should be emphasized.

In conclusion, I pose the following suppose experiment to the reader, assumed to be the manager of a complex nuclear system operating in space: generate a carpet plot and ask your ten year old child some numerous questions, such as: I have designed a system for a predicted thermal conductivity, tank diameter, percent LH_2 slush, density, weight penalty, temperature levels, and manufacturing cost. Due to installation problems, the thickness, (layer density) changes from this to that. What will be the effect upon mission time? (My daughter loves to solve the 100 or so combinations of results with a school ruler.)

"A picture is worth a thousand words" applies to this technique.

References

1. Theories of Engineering Experimentation, 2nd Edition, Hilbert Schenk, Jr.
2. "Air Breathing Engines," Short Course on Air-Breathing Engine Technology, 8-12 June, 1970, Marshall Space Flight Center, Alabama.

$$WP = \frac{\rho \, A \, \Delta X}{\rho_H \, V}$$

$$\theta = \frac{\rho (\Delta X)^2 \, hfg}{K \, \Delta T}$$

VARIABLES

1. BOUNDARY TEMPERATURES
2. INSULATION THICKNESS
3. INSULATION DENSITY
4. MISSION TIME
5. WEIGHT PENALTY
6. THERMAL CONDUCTIVITY
7. VENT PRESSURE
8. PERCENT SLUSH
9. L/D RATIO
10. DESIGN BASIS
11. VEHICLE DIAMETER

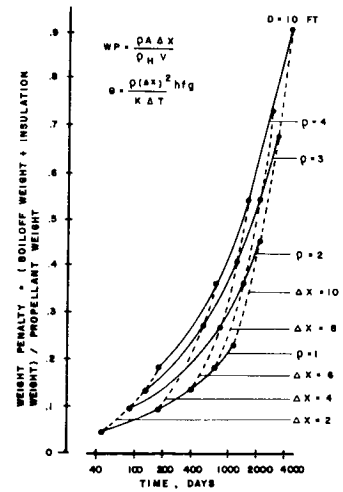Table 1. Properties considered in the study

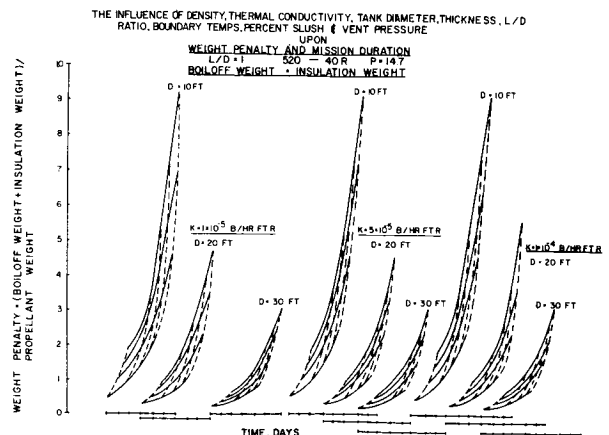Figure 14. The effect of several variables upon the performance of a nuclear-powered space vehicle

Figure 15. Extension of Fig. 14 to account for additional variables