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PROFILE: A RAIL HUMP CLASSIFICATION YARD GRADIENT SIMULATION

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ABSTRACT

Designers of rail hump yards traditionally go through a tedious, long manual process to optimally design the hump grades and retarder placements. This design process involves checking velocities and headways of a worst case sequence of cars to insure that proper values of these variables can be maintained on the gradient. This paper presents a computer simulation model, PROFILE, that automatically computes these quantities, thus freeing the designer of tedious work and allowing him to generate and study more design alternatives. The model uses the usual static (velocity indpendent) rolling resistance formulation of car rollability, but in addition offers the option of a velocity dependent rolling resistance model. The paper gives descriptions of user input requirements and program-generated output. Finally, the paper gives an example of the model's application to a real-life design problem.

Introduction

Rail hump yards perform classification by rolling a cut of cars down a grade and switching the cars into various class tracks. To perform switching properly, sufficient headway between cars must be created and maintained. The main problem in the design of the hump profile and in the development of an effective speed control scheme is to ensure that the headway maintained in the switching area is sufficient to throw switches (e.g., 50 ft) and prevent catch-up in retarders, that speed restrictions at switches and curves are observed (e.g. 15 mph), and that proper coupling occurs on the class tracks within specified speed limits (e.g., 2 mph to 6 mph). Controlling headway and speeds would not be difficult if all cars had identical characteristics and rolling resistances (i.e., rollability) since the initial time separation established at the crest would result in a uniform and predictable headway between cars.

However, car rollability is not uniform; it varies with weather, type of car, and changes during a car's roll. Nonetheless, it is incumbant on the profile designer that a large percentage of the cars (e.g. 99.9%) be delivered to the bowl tracks in a manner satisfying the above design constraints. Indeed, since car speed is directly translatable into hump throughput, it is desirable that the fastest car speeds meeting these constraints be employed.

These aims are usually approached based on assuming hardest (slowest) and easiest (fastest) rolling cars. Hump grades are usually designed to deliver the hardest rolling car to the clear point at a specified speed (say, 4 mph) or to a specified distance into the class track (e.g., 500 ft). The sizing and placement of retarder sections is usually accomplished by examining a worst-case triplet of a design hardest rolling car followed by a design easiest rolling car followed by a design hardest rolling car traveling to the last switch on the farthest outside track. The retarders are placed where the separation between the two lead cars become less than a specified value; the retarder slows down the second car to reestablish proper headway. The length (power) of the retarder is based on the amount of energy that must be removed from the second car in this worst-case situation. At the same time, caution must be excercised to insure that the second (easiest rolling) car is not slowed so much that the third (hardest rolling) car catches it.

It is the purpose of the PROFILE model to provide the yard designer with an iterative and interactive computer design tool that will enable the designer to perform such an analysis, insuring that the above constraints are satisfied. The need for some automation of the hump design procedure has long been recognized. The labor and man hours involved in tediously plotting velocity head diagrams, converting these to car velocity, integrating velocity of cars to obtain time-distance plots, and finally comparing time-distance plots of cars to obtain headway have acted to severely restrict the number of design alternatives that could be considered by the yard designer. It is the intent of the PROFILE simulation model to automate this process; this automation also offers the designer the option of selecting a more advanced car rollability model (over the usual static rolling resistance formulation) if desired.

PROFILE does not automate the entire yard design process or replace the designer; rather it extends the abilities of the designer by, in comparison to the manual process, permitting him to evaluate many more design alternatives in shorter time.

The PROFILE model has been used to support yard design efforts by three railroads: Boston and Maine, Conrail, and Union Pacific.

Overview of the Model

PROFILE is a one-track simulation, i.e. the user selects one route from the crest to the bowl and simulates only that route in a run. With repeated runs, all routes to the bowl can be simulated, if needed. The profile gradient along this route is represented as a series of track sections. All parameters are assumed to be constant within a given track section.

Only single car cuts are modelled, although longer cuts can be approximated as a single car of unusual length.

Within each track section, each car is treated for the purpose of its dynamics as a point mass whose motion is assumed to be governed by the following differential equation:

$$\frac{d^2X}{dt^2} = \frac{dV}{dt} = \alpha + \beta V \qquad (1)$$

$$\alpha = g_e \left(\sin\theta - \mu - C - W - \frac{S}{L} - \frac{R}{L}\right) \qquad (2)$$

$$\beta = g_e \left(-\mu_V - W_V\right) \qquad (3)$$

$$g_e = \left[\frac{T}{T + I}\right] g \qquad (4)$$

where

X = Distance from an arbitrary origin, m (ft)

V = Velocity of the car, m/sec (ft/sec)

t = time, sec

α = Sum of all static terms contributing to the car's acceleration, m/sec^2 (ft/sec^2)

β = Sum of all velocity dependent terms contributing to the car's acceleration, sec^{-1}

g_e = Effective acceleration of gravity used to account for energy stored in the rotating wheels of the car, m/sec^2 (ft/sec^2)

g = Acceleration of gravity, m/sec^2 (ft/sec^2)

T = Weight of the car, kg (lb)

I = Additional weight of the car to account for the rotation of the wheels, kg (lb)

θ = Angle of the grade below horizontal

$\sin\theta \cong \tan\theta$ = Grade (downgrades taken positive), m/m (ft/ft)

μ = Static rolling resistance, kg/kg (lb/lb)

C = Curve resistance (If the track section is on a curve), kg/kg (lb/lb)

W = Wind resistance, kg/kg (lb/lb)

S = Velocity head lost in switch (If the track section is a switch), m (ft)

R = Velocity head extracted by retarder (If the track section is a retarder), m (ft)

L = Length of track section, m (ft)

μ_V = Velocity-dependent resistance coefficient kg/kg per m/sec (lb/lb per ft/sec)

W_V = Velocity-dependent wind resistance coefficient, kg/kg per m/sec (lb/lb per ft/sec)

Obviously, in any given track section, not all the terms will be applicable. For example, a conventional retarder and a switch would never be found in the same track section. The various parameters are assumed to be constant within each track section. Whenever any one or more parameters change, a new track section must be specified. This happens, for example, when specifying the beginning and end of a retarder. A new track section is also required whenever the grade changes. Vertical curves are approximated by a series of track sections of constant grade.

The solution of the differential equation, for $\beta \neq 0$ and taking $V = V_o$ and $X = X_o$ at $t = 0$, is

$$V = -\frac{\alpha}{\beta} + \left(\frac{\alpha}{\beta} + V_o\right) \exp(\beta t) \tag{5}$$

$$X = X_o - \frac{\alpha}{\beta} t - \frac{1}{\beta} \left(\frac{\alpha}{\beta} + V_o\right) (1 - \exp(\beta t)) \tag{6}$$

For $\beta = 0$ (i.e. only static rolling resistance), the solution reduces to the well known case of uniformly accelerated motion, with solution (for the above boundary conditions)

$$V = V_o + \alpha t \tag{7}$$

$$X = X_o + V_o t + \frac{1}{2} \alpha t^2 \tag{8}$$

The $\beta = 0$ case is, of course, the usual static rolling resistance formulation, for which computational techniques based on energy relationships are well developed. However, though these energy relationships are easily applied to obtain velocity, it can become tedious to integrate the velocities over a varying grade to obtain distance-time plots and hence headways between cars. Even when a static rolling resistance formulation is being used, the utility of using PROFILE as a quick calculator is great.

A word is required about the treatment of wind resistance. Although wind resistance would usually be handled by a V^2 term, here only a V term is used. At the low speeds in a hump yard, it is felt that the curvature of a V^2 relation will be sufficiently slight that it can be satisfactorily approximated by a linear term.

A word is also required about the way retarders are modeled. The retarders treated in the present version of PROFILE are the conventional clasp type, usually controlled by a process control computer. PROFILE, at the moment, does not consider the distributed types of retarders offering quasi-continuous control through purely mechanical analog logic systems (as offered by certain European vendors). The conventional retarder system is quite complex, with the process control computer controlling both the overall amount of retardation, as well as the detailed dynamics of the car-retarder interactions while the car is within the retarder. Several algorithms are in use to decelerate the car within the retarder. They are all based upon the idea of achieving a desired exit speed from the retarder. The algorithms can be roughly catagorized into three types (see Figure 1):

1. Retardation at Earliest Moment. This is probably the most common retarder control algorithm (1, 2, 3). The retarder closes as soon as the car enters; when the car reaches the exit velocity, the retarder opens, and the car either rolls freely for the rest of the length of the retarder, or the retarder opens and closes in an attempt to maintain the car at approximately the desired exit speed. This scheme tends to restrict hump throughput, since the car's average speed for the length of the retarder is at a minimum. It also causes a disproportionate amount of the retarder wear to occur near the front.

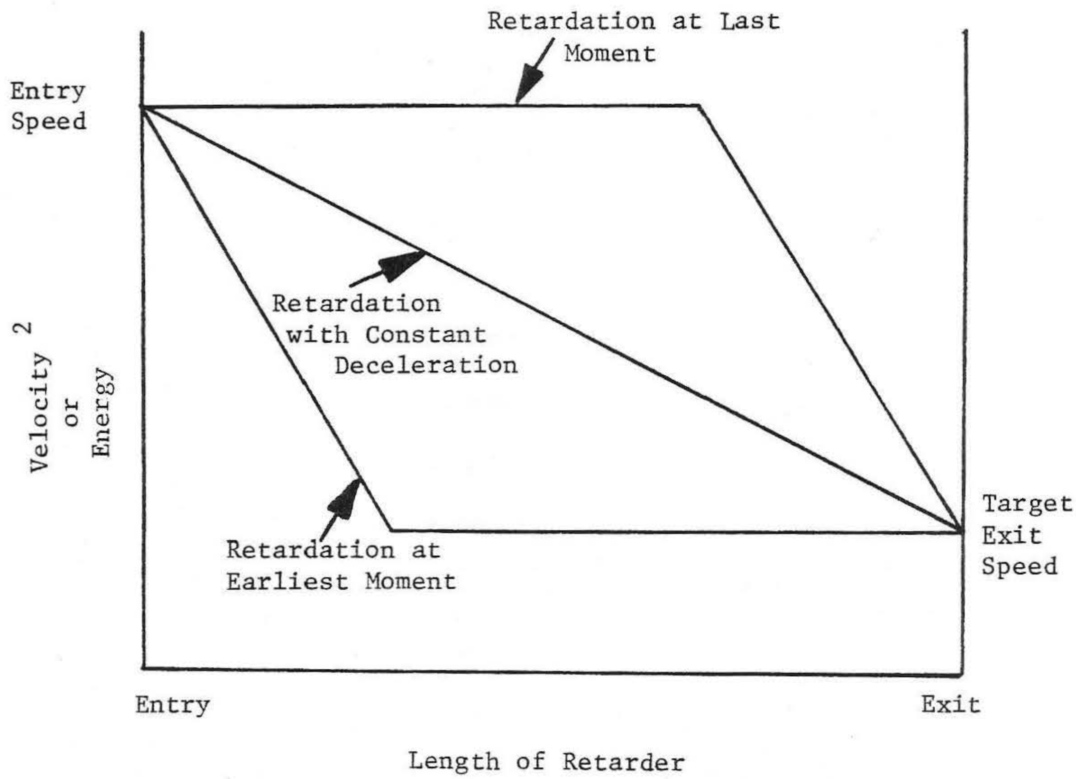


Figure 1 - Schematic Diagram of Retarder Deceleration Algorithms

2. Retardation at last moment (1). When the car enters the retarder, the retarder initially remains open. Based upon a prediction of the car's rollability and the retarder's power, the algorithm closes the retarder at just that time which, according to the prediction, will achieve the desired exit velocity. This scheme generally permits a high throughput since the car's average speed throughout the retarder is at a maximum. However, it lacks a safety margin in case the car rolls faster than predicted, due to rollability prediction errors, grease on the wheels or rails, or such. This algorithm also causes a disproportionate amount of the retarder wear to occur near the rear of the retarder.
3. Retardation with constant deceleration. Under this algorithm, the retarder either is commanded to open and close several times (4) or exerts a constant retardation force (2), in either case the aim being to achieve the desired exit speed with approximately constant deceleration. Some commercial, modern retarder systems achieve this ideal at least approximately (5). This scheme maintains better throughput than scheme (1), yet also maintains a safety reserve of retarder power lacking in scheme (2). It also causes the retarder to wear approximately uniformly throughout.

In the PROFILE model, the third type of deceleration scheme is assumed to apply, i.e. constant deceleration. Under constant deceleration, energy (i.e. velocity head) is extracted at a uniform rate during the course of the car's transit of the retarder. Under this assumption, the total amount of velocity head extracted within the retarder, when divided by the retarder length, acts simply as an additional resistance term; hence the form of its appearance of Equation 2.

Program Description

PROFILE is a time-step simulation written in ANSI standard Fortran. Events are assumed to take place either at integral multiples of a predetermined time step, Δt, or, for certain easily calculated events (such as car's entry into a new track section), within the time step. The time-step method has been selected because of the ease afforded in solving transcendental and other solutions to differential equations.

The simulation starts by humping the first car at simulation clock time zero. From the length of the involved cars and the hump speed, the hump time for the second car is computed and stored until the simulation clock is equal to that hump time or greater. At the calculated hump time the second car gets humped and put into the system. Again the hump time for the third car is computed and so on until all cars that the user wishes to put into the system are humped.

Once a car has been humped movement of cars along the track is accomplished by advancing the simulation clock in increments of Δt. At each time step the linear differential equation (1) is solved for the instantaneous velocities and the distances of cars along the track. Each time a car enters a new track section, the program solves an initial-value problem based on the general solution to the differential equation and the specified configurations of the new track segment. These coefficients will be used in subsequent calculations of this particular car on this track at steps of Δt until the car leaves this track section.

At each time step, the coupler-to-coupler headways between the cars in the system are checked. This is done to maintain a safe operating distance beween the cars and to avoid misswitching, catch-up in retarders, and collisions. If an insufficient headway occurs the program will write a warning message to the output file. If a collision occurs or a car stalls, the program stops and writes a message to the output file. These messages show the simulation clock time at which the catch-up occurred, the distance along the track for each car, and their velocities at this time. The user may then analyze the output and make changes to retarder placements, length of the retarder, or any other parameter and start a new computer iteration.

Data on each car are collected at each print interval as specified by the user. For each car the simulation clock time, the instantaneous velocity, the velocity head, the distance from the hump crest and the distance and time headways from the preceding car are written to and stored in a print buffer. Data in the buffer is written to the output file whenever the simulation comes to a stop. If no collision or stall occurs, the simulation comes to stop when the last car has come to the end of the last track section. A sample partial output is given in Figures 2 through 6.

Description of Input

A complete list of input variables is given in Table 1. First, the time step (Δt), the hump speed, the data print interval, and some program control switches are given. To model event occurrences accurately, the time step should be chosen sufficiently small but not too small as to cause an inordinate increase in running time. One second is usually satisfactory. Data output frequency is controlled by the data print interval variable.

SRI HUMP PROFILE SIMULATION - YERMO NO. 8 FILE - TRIAL RUN 1 - RETARDATION FOR SPEED CONTROL ONLY

SIMULATION TIME STEP, DELTA T, SEC	1.0000
HUMP SPEED, MILES PER HOUR	2.5000
DATA PRINT INTERVAL, SEC	1.00
TABLE SWITCH	1
PLOT SWITCH	1
PRINTER WIDTH (CHARACTERS)	132

T R A C K   D A T A

TRK SEC NO.	LENG (FT)	CUM. LENG (FT)	GRADE (PCT)	RESISTANCES: ROLLING: STATIC (LB/TON) EASY	STATIC (LB/TON) HARD	VELOCITY (LB/TON)/(FT/SEC) EASY	VELOCITY (LB/TON)/(FT/SEC) HARD	HORIZ. CURVE (LB/T)	SWITCH LOSS (FT OF VELOC. HEAD)	RETARDATION (FT. OF VEL. HEAD) CAR 1	CAR 2	CAR 3	MAX. RETARDATION (FT OF VELOC. HEAD)	DESCRIPTION
1	50.0	0.0	3.00	4.00	18.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	CREST TO EVC
2	71.0	50.0	4.23	4.00	18.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	EVC TO M. RET.
3	93.0	121.0	3.99	4.00	18.00	-0.00	-0.00	-0.00	-0.00	0.00	.80	0.00	6.72	MASTER RET.
4	24.0	214.0	1.44	4.00	18.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	M. TO KING SW.
5	1.0	238.0	1.44	4.00	18.00	-0.00	-0.00	-0.00	.06	-0.00	-0.00	-0.00	-0.00	KING SW
6	25.0	239.0	.50	4.00	18.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	KING SW TO LAP
7	1.0	264.0	.50	4.00	18.00	-0.00	-0.00	-0.00	.06	-0.00	-0.00	-0.00	-0.00	LAP SW
8	100.0	265.0	.50	4.00	18.00	-0.00	-0.00	11.30	-0.00	-0.00	-0.00	-0.00	-0.00	LAP SW TO PT
9	95.0	365.0	.50	4.00	18.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	PT TO GR. RET.
10	100.0	460.0	1.20	4.00	18.00	-0.00	-0.00	-0.00	-0.00	0.00	5.24	0.00	6.72	GR. RET.
11	17.0	560.0	.10	2.00	10.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	GR TO LAP 2
12	1.0	577.0	.10	2.00	10.00	-0.00	-0.00	-0.00	.06	-0.00	-0.00	-0.00	-0.00	LAP 2
13	70.0	578.0	.10	2.00	10.00	-0.00	-0.00	5.25	-0.00	-0.00	-0.00	-0.00	-0.00	LAP 2 TO HF 2
14	28.0	648.0	.10	2.00	10.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	HF 2 TO SW 3
15	1.0	676.0	.10	2.00	10.00	-0.00	-0.00	-0.00	.06	-0.00	-0.00	-0.00	-0.00	SW 3
16	70.0	677.0	.10	2.00	10.00	-0.00	-0.00	5.25	-0.00	-0.00	-0.00	-0.00	-0.00	SW 3 TO HF 3
17	30.0	747.0	.10	2.00	10.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	HF 3 TO SW 4
18	1.0	777.0	.10	2.00	10.00	-0.00	-0.00	-0.00	.06	-0.00	-0.00	-0.00	-0.00	SW 4
19	70.0	778.0	.10	2.00	10.00	-0.00	-0.00	5.25	-0.00	-0.00	-0.00	-0.00	-0.00	SW 4 TO HF 4
20	68.0	848.0	.10	2.00	10.00	-0.00	-0.00	12.25	-0.00	-0.00	-0.00	-0.00	-0.00	HF 4 TO CLEAR
21	145.0	916.0	.10	2.00	10.00	-0.00	-0.00	12.25	-0.00	-0.00	-0.00	-0.00	-0.00	CLEAR TO POT
22	15.0	1061.0	.10	2.00	10.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	POT TO PTT
23	300.0	1076.0	.08	2.00	10.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	PTT TO END

C A R   D A T A

TYPE OF ROLLER, 1 = EASY, 2 = HARD

CAR NO.	TYPE ROLLER	CAR LENGTH (FT)	WEIGHT OF CAR (TONS)	EXTRA WEIGHT WHEEL ROTATION (TONS)	WIND RESIS STAT (LB/T)	WIND RESIS VELOC (LB/T)/(FPS)
1	2	60.00	64.00	1.00	-0.00	-0.00
2	1	60.00	135.00	1.00	-0.00	-0.00
3	2	60.00	64.00	1.00	-0.00	-0.00

A COLLISION OCCURRED AT TIME 116.40 SEC. BETWEEN
CAR 1 - VEL = 2.27 MPH, DIST = 1336.30 FT., TIME ON TRACK = 116.40 SEC.
CAR 2 - VEL = 5.89 MPH, DIST = 1276.30 FT., TIME ON TRACK = 100.04 SEC.

Figure 2 - Echo Back and Collision Information for Trial Run 1 of Yermo Yard

SRI HUMP PROFILE SIMULATION - YERMO NO. 8 FILE - TRIAL RUN 2 - ELIMINATE MASTER RETARDER

SIMULATION TIME STEP, DELTA T, SEC	1.0000
HUMP SPEED, MILES PER HOUR	2.5000
DATA PRINT INTERVAL, SEC	1.00
TABLE SWITCH	1
PLOT SWITCH	1
PRINTER WIDTH (CHARACTERS)	132

T R A C K   D A T A

TRK SEC NO.	LENG (FT)	CUM. LENG (FT)	GRADE (PCT)	RESISTANCES: ROLLING: STATIC (LB/TON) EASY	STATIC (LB/TON) HARD	VELOCITY (LB/TON)/(FT/SEC) EASY	VELOCITY (LB/TON)/(FT/SEC) HARD	HORIZ. CURVE (LB/T)	SWITCH LOSS (FT OF VELOC. HEAD)	RETARDATION (FT. OF VEL. HEAD) CAR 1	CAR 2	CAR 3	MAX. RETARDATION (FT OF VELOC. HEAD)	D E S C R I P T I O N
1	50.0	0.0	3.00	4.00	18.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	CREST TO EVC
2	71.0	50.0	4.23	4.00	18.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	EVC TO FORMER M. RET.
3	72.0	121.0	3.99	4.00	18.00	-0.00	-0.00	-0.00	-0.00	0.00	0.00	0.00	6.72	FORMER MASTER RET.
4	24.0	193.0	1.44	4.00	18.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	FORMER M. RET. TO KING SW.
5	1.0	217.0	1.44	4.00	18.00	-0.00	-0.00	-0.00	.06	-0.00	-0.00	-0.00	-0.00	KING SW
6	25.0	218.0	.50	4.00	18.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	KING SW TO LAP
7	1.0	243.0	.50	4.00	18.00	-0.00	-0.00	-0.00	.06	-0.00	-0.00	-0.00	-0.00	LAP SW
8	100.0	244.0	.50	4.00	18.00	-0.00	-0.00	11.30	-0.00	-0.00	-0.00	-0.00	-0.00	LAP SW TO PT
9	95.0	344.0	.50	4.00	18.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	PT TO GR. RET.
10	100.0	439.0	1.20	4.00	18.00	-0.00	-0.00	-0.00	-0.00	0.00	5.24	0.00	6.72	GR. RET.
11	17.0	539.0	.10	2.00	10.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	GR TO LAP 2
12	1.0	556.0	.10	2.00	10.00	-0.00	-0.00	-0.00	.06	-0.00	-0.00	-0.00	-0.00	LAP 2
13	70.0	557.0	.10	2.00	10.00	-0.00	-0.00	5.25	-0.00	-0.00	-0.00	-0.00	-0.00	LAP 2 TO HF 2
14	28.0	627.0	.10	2.00	10.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	HF 2 TO SW 3
15	1.0	655.0	.10	2.00	10.00	-0.00	-0.00	-0.00	.06	-0.00	-0.00	-0.00	-0.00	SW 3
16	70.0	656.0	.10	2.00	10.00	-0.00	-0.00	5.25	-0.00	-0.00	-0.00	-0.00	-0.00	SW 3 TO HF 3
17	30.0	726.0	.10	2.00	10.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	HF 3 TO SW 4
18	1.0	756.0	.10	2.00	10.00	-0.00	-0.00	-0.00	.06	-0.00	-0.00	-0.00	-0.00	SW 4
19	70.0	757.0	.10	2.00	10.00	-0.00	-0.00	5.25	-0.00	-0.00	-0.00	-0.00	-0.00	SW 4 TO HF 4
20	68.0	827.0	.10	2.00	10.00	-0.00	-0.00	12.25	-0.00	-0.00	-0.00	-0.00	-0.00	HF 4 TO CLEAR
21	145.0	895.0	.10	2.00	10.00	-0.00	-0.00	12.25	-0.00	-0.00	-0.00	-0.00	-0.00	CLEAR TO POT
22	15.0	1040.0	.10	2.00	10.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	POT TO PTT
23	300.0	1055.0	.08	2.00	10.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	PTT TO END

C A R   D A T A

TYPE OF ROLLER, 1 = EASY, 2 = HARD

CAR NO.	TYPE ROLLER	CAR LENGTH (FT)	WEIGHT OF CAR (TONS)	EXTRA WEIGHT WHEEL ROTATION (TONS)	WIND RESIS STAT (LB/T)	WIND RESIS VELOC (LB/T) /(FPS)
1	2	60.00	64.00	1.00	-0.00	-0.00
2	1	60.00	135.00	1.00	-0.00	-0.00
3	2	60.00	64.00	1.00	-0.00	-0.00

A COLLISION OCCURRED AT TIME 93.82 SEC. BETWEEN
CAR 1 - VEL = 3.02 MPH, DIST = 1129.01 FT., TIME ON TRACK = 93.82 SEC.
CAR 2 - VEL = 6.00 MPH, DIST = 1069.01 FT., TIME ON TRACK = 77.45 SEC.

Figure 3 - Echo Back and Collision Information for Trial Run 2 of Yermo Yard

CAR NO. 2

CAR TRAVEL TIME (SEC)	SYSTEM TIME (SEC)	DISTANCE ALONG TRACK (FT)	DISTANCE HEADWAY BETWEEN PREC CAR (FT)	TIME HEADWAY BETWEEN PREC CAR (SEC)	INSTANTANEOUS VELOCITY (FT/SEC)	INSTANTANEOUS VELOCITY (MPH)	VELOCITY HEAD (FT)	TRACK SECTION NUMBER	TRACK SECTION DESCRIPTION
0.000	16.364	0.000	102.770	7.382	3.667	2.500	.210	0/ 1	****TRACK SECTION BOUNDARY****
.636	17.000	2.515	111.691	7.772	4.236	2.888	.281	1	CREST TO EVC
1.636	18.000	7.198	125.778	8.328	5.131	3.499	.412	1	CREST TO EVC
2.636	19.000	12.777	139.547	8.823	6.026	4.109	.568	1	CREST TO EVC
3.636	20.000	19.250	152.447	9.266	6.921	4.719	.749	1	CREST TO EVC
4.636	21.000	26.619	164.261	9.663	7.816	5.329	.956	1	CREST TO EVC
5.636	22.000	34.883	174.850	10.022	8.711	5.939	1.187	1	CREST TO EVC
6.636	23.000	44.041	184.238	10.347	9.606	6.550	1.443	1	CREST TO EVC
7.240	23.603	50.000	189.322	10.530	10.146	6.918	1.610	1/ 2	****TRACK SECTION BOUNDARY****
7.636	24.000	54.126	192.394	10.642	10.657	7.266	1.777	2	EVC TO FORMER M. RET.
8.636	25.000	65.427	199.028	10.892	11.945	8.145	2.232	2	EVC TO FORMER M. RET.
9.636	26.000	78.016	204.067	11.097	13.234	9.023	2.740	2	EVC TO FORMER M. RET.
10.636	27.000	91.894	207.583	11.263	14.522	9.901	3.299	2	EVC TO FORMER M. RET.
11.636	28.000	107.060	209.683	11.395	15.810	10.779	3.910	2	EVC TO FORMER M. RET.
12.489	28.852	121.000	210.356	11.484	16.908	11.528	4.472	2/ 3	****TRACK SECTION BOUNDARY****
12.636	29.000	123.513	210.369	11.498	17.087	11.651	4.567	3	FORMER MASTER RET.
13.636	30.000	141.206	209.688	11.574	18.299	12.477	5.238	3	FORMER MASTER RET.
14.636	31.000	160.111	207.669	11.599	19.510	13.302	5.955	3	FORMER MASTER RET.
15.636	32.000	180.227	204.324	11.557	20.722	14.128	6.717	3	FORMER MASTER RET.
16.242	32.606	193.000	201.725	11.494	21.456	14.629	7.201	3/ 4	****TRACK SECTION BOUNDARY****
16.636	33.000	201.491	199.877	11.439	21.612	14.735	7.306	4	FORMER M. RET. TO KING SW.
17.349	33.713	217.000	196.415	11.323	21.895	14.928	7.499	4/ 5	****TRACK SECTION BOUNDARY****
17.395	33.759	218.000	196.189	11.315	21.825	14.881	7.451	5/ 6	****TRACK SECTION BOUNDARY****
17.636	34.000	223.269	195.010	11.272	21.848	14.896	7.467	6	KING SW TO LAP
18.538	34.901	243.000	190.603	11.096	21.935	14.955	7.526	6/ 7	****TRACK SECTION BOUNDARY****
18.583	34.947	244.000	190.381	11.086	21.851	14.899	7.469	7/ 8	****TRACK SECTION BOUNDARY****
18.636	35.000	245.158	190.127	11.075	21.847	14.896	7.466	8	LAP SW TO PT
19.636	36.000	266.962	185.424	10.859	21.762	14.838	7.408	8	LAP SW TO PT
20.636	37.000	288.682	180.901	10.622	21.677	14.780	7.351	8	LAP SW TO PT
21.636	38.000	310.317	176.535	10.373	21.593	14.722	7.293	8	LAP SW TO PT
22.636	39.000	331.868	172.104	10.118	21.508	14.665	7.236	8	LAP SW TO PT
23.201	39.565	344.000	169.520	9.971	21.460	14.632	7.204	8/ 9	****TRACK SECTION BOUNDARY****
23.636	40.000	353.351	167.483	9.855	21.502	14.660	7.232	9	PT TO GR. RET.
24.636	41.000	374.900	162.585	9.576	21.598	14.726	7.297	9	PT TO GR. RET.
25.636	42.000	396.546	157.381	9.286	21.694	14.791	7.362	9	PT TO GR. RET.
26.636	43.000	418.288	151.873	8.999	21.790	14.857	7.427	9	PT TO GR. RET.
27.585	43.949	439.000	146.416	8.731	21.881	14.919	7.489	9/10	****TRACK SECTION BOUNDARY****
27.636	44.000	440.124	146.116	8.717	21.811	14.871	7.442	10	GR. RET.
28.636	45.000	461.257	140.879	8.484	20.456	13.947	6.546	10	GR. RET.
29.636	46.000	481.035	136.734	8.337	19.100	13.023	5.707	10	GR. RET.
30.636	47.000	499.458	133.733	8.266	17.745	12.099	4.926	10	GR. RET.
31.636	48.000	516.525	131.878	8.257	16.390	11.175	4.202	10	GR. RET.
32.636	49.000	532.237	131.168	8.317	15.035	10.251	3.536	10	GR. RET.
33.096	49.459	539.000	131.229	8.368	14.412	9.827	3.249	10/11	****TRACK SECTION BOUNDARY****
33.636	50.000	546.793	131.433	8.435	14.412	9.827	3.249	11	GR TO LAP 2
34.275	50.639	556.000	131.627	8.512	14.412	9.827	3.249	11/12	****TRACK SECTION BOUNDARY****
34.345	50.709	557.000	131.649	8.520	14.279	9.736	3.189	12/13	****TRACK SECTION BOUNDARY****
34.636	51.000	561.158	131.760	8.556	14.255	9.719	3.179	13	LAP 2 TO HF 2

Figure 4 - Example of Car History Table - Partial Output for Car No. 2 (Easy Roller) for Trial Run 2 of Yermo Yard

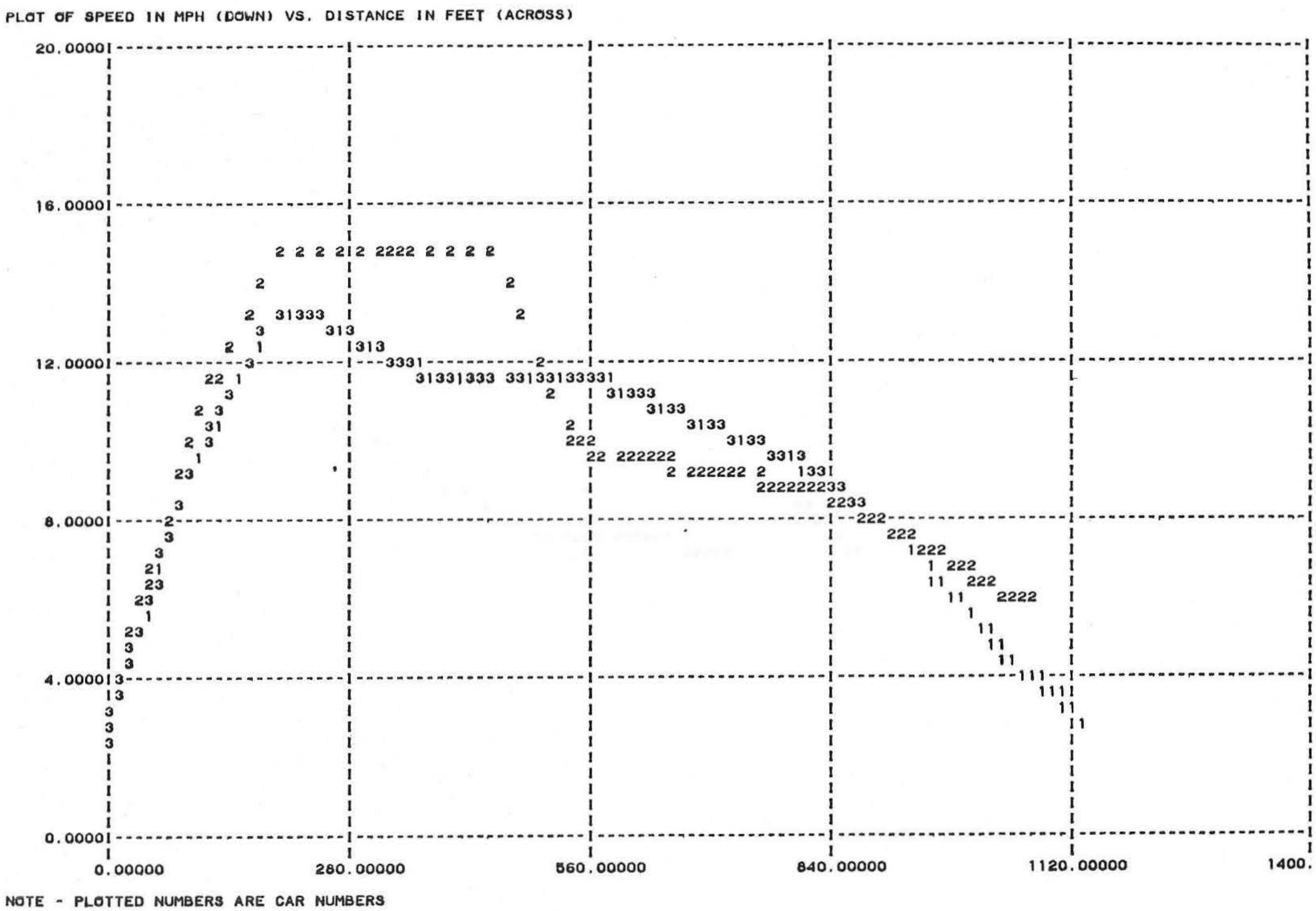
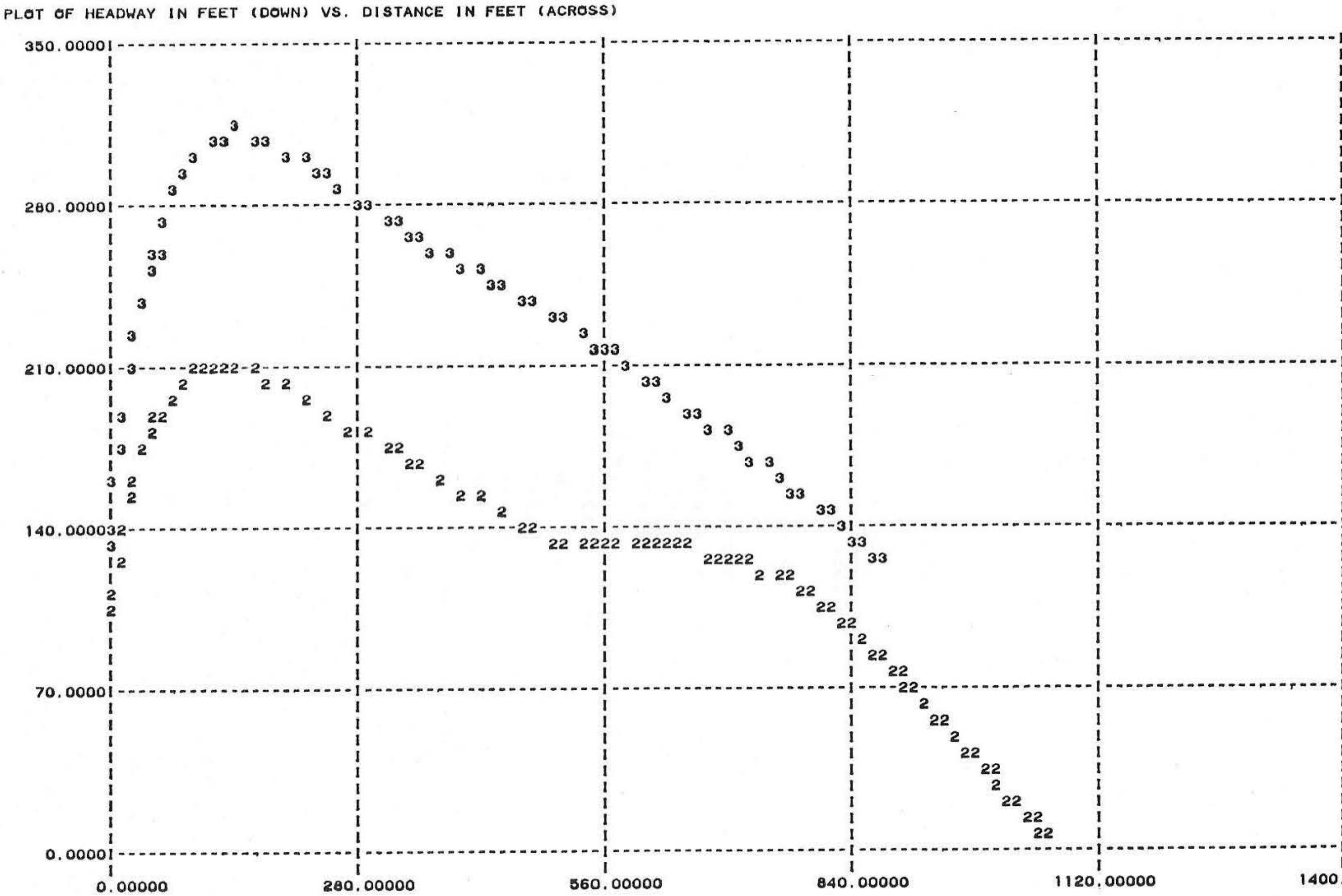


Figure 5 - Plot of Speed Versus Distance
for Trial Run 2 of Yermo Yard



PLOT LEGEND -

HEADWAY BT. CARS	PLOTTED NO.
1 AND 2	2
2 AND 3	3

Figure 6 - Plot of Distance Headway versus Distance
for Trial Run 2 of Yermo Yard

TABLE 1

PROFILE INPUT

GENERAL INPUT PARAMETERS

Time Step, Δt, sec.
Hump speed, miles per hour
Data print interval
Table switch
Plot switch
Printer width, characters

TRACK SECTION DESCRIPTIONS (One set of descriptions for each track section)

Length of track section, ft.
Grade of track, percent
Rolling resistance, static, easy roller (lb/ton)
Rolling resistance, static, hard roller (lb/ton)
Rolling resistance, velocity, easy (lb/ton)/(ft/sec)
Rolling resistance, velocity, hard (lb/ton)/ft/sec)
Switch loss, feet of velocity head
Amount of retardation to be given easy rolling car, feet of velocity head
Amount of retardation to be given hard rolling car, feet of velocity head
Maximum retardation of the retarder, feet of velocity head
Track section alphanumeric identification

CAR DESCRIPTIONS (One set of descriptions for each simulated car)

Type of roller, easy or hard
Car length, ft.
Weight of car (tons)
Equivalent rotational weight of all the wheels (tons)
Wind resistance, static (lb/ton)
Wind resistance, velocity (lb/ton)/(ft/sec)

This variable should be chosen in integral multiples of the time step but never less than the time step.

Next, the data for the track sections is specified. The static and velocity resistances can be specified separately for each track section for the two types of car: Easy roller or hard roller. The length of track and percent of grade are also specified for each track section. If the track segment is a retarder section, additional parameters are required. These are the retardation in feet of head to be given each car and the maximum velocity head the retarder can extract.

Data for the cars constitute the final set of information specified to the program. First, the type of car must be specified (easy or hard rolling). Then the car length, the weight of the car and an equivalent rotational weight for the wheels must be given. Each car is associated with static and velocity dependent wind resistance terms. These values may vary depending on the type of car (box car, flat car, gondola, etc.).

Description of Output

The output from PROFILE consists of three parts. A sample, partial output is given in Figures 2 through 6.

The first of the output consists of an "echo-back" of the input data (Figures 2 and 3). This is simply a listing of the user's input given for documentation and verification.

Next, the numerical output from the simulation proper is given. This consists of a series of tables, one table for each car. The contents of this table have already been described. An example of a portion of this table is presented in Figure 4. Each line in a table gives a number of variables defining the status of that particular car at a point in time. The lines are generally printed at uniform increments of simulated time, although whenever a car enters a new track section an additional line is printed. The print increment is specified by the user and is usually on the order of one second.

The third and last output section gives optional line printer plots of selected variables. These plots, which include relevant annotation, consist of:

- A plot of the yard profile versus distance.
- A plot of speeds of all cars versus distance (Figure 5).
- A plot of distance headways between all cars versus distance (Figure 6).

Application of the Model to a Real-World Problem

The example application problem described in this section in one of several trial designs being studied for the Union Pacific Railroad's Yermo Yard in Southern California.

The hump profile design requires several levels of decision making on cost and performance related matters. The considerations on the cost and the performance would be reflected on the retarder types to be used, the hump crest height, the humping speed, the impact speed, and the number of misswitched cars. After having determined the type of retarder and retarder configuration to be adopted, the designer must go through the tedious process of going back and forth between the horizontal and vertical design to come up with a final design which satisfies the design goal.

The application problem discussed here is only one stage of the hump profile design process, in which a given profile design is evaluated and modified to a better design through iterations of PROFILE runs.

The retarder configuration which is used in this example has a master retarder of 28.3 m (93 feet) and three group retarders of 30.5 m (100 feet). Each group retarder leads to ten classification tracks. The distance between the hump crest and the tangent point of the outer most track is 323.4 m (1061 feet). The basic geometric design along the outer most track for Trial Run 1 is given in the "echo back output" produced by PROFILE in Figure 2.

The runs for this design were based on the simulation of a conventional Hard-Easy-Hard rolling triplet of cars, as explained previously in this paper. A worst case condition was assumed -- the easy rolling car going to a nearly full class track (so that it has to be retarded to a low target speed by the tangent point, 9.6 kph (6 mph) while the hard rolling car must penetrate an adjacent empty class track as far as possible (so that its retardation is minimal).

The objective of the study is to test the feasibility of the design by examining the design requirements such that:

- The hump speed is at least 4.0 kph (2.5 mph, 3.67 cars/min).
- The hard roller must not stall before the tangent point.
- The speed of the easy roller at the tangent point is at most 9.6 kph (6 mph).
- The maximum speed of a car in the switch segments is 24 kph (15 mph).
- There should be a coupler-to-coupler headway of at least 15.2 m (50 feet) at each switch.
- There should be no catch-ups before the clearance point of each track.

The major assumptions used in the design process are:

- Only static rolling resistances apply.
- The hard roller has a rolling resistance of 9 kg/metric ton (18 lbs/ton) between the hump crest and the exit from the group retarders, and 5 kg/metric ton (10 lbs/ton) thereafter.
- The easy roller has a rolling resistance of 2 kg/metric ton (4 lbs/ton) between the hump crest and the exit from the group retarder, and 1 kg/metric ton (2 lbs/ton) thereafter.
- The velocity head loss due to each switch is .018 m (.06 feet) when the car travels along the curved track. The velocity head loss is assumed zero if a car travels on the straight track. This value is constant for all turnout numbers.
- The velocity head loss due to a curved section of track is .012 m (.04 feet) per degree of deflection angle.
- The average car length is 18.3 m (60 ft).
- The average car weight is 58 metric tons (64 tons) for the hard roller and 122 metric tons (135 tons) for the easy roller.
- The extra weight of the car due to wheel rotation is .91 metric tons (1.00 tons).
- The wind resistance is zero.

A general interactive and iterative design procedure* was used in this example design. The steps in this procedure are as follows:

1. Select the retarder configuration, retarder type, and retardation method.
2. Determine the car speed constraints at the tangent point and other points along the track.

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*Other procedures, not shown here, enable the user using PROFILE to select a hump speed and a retarder control policy.

3. Design a trial horizontal layout.

4. Determine the hump height from 2 and 3.

5. Select the trial grades along the track.

6. Run PROFILE.

7. Examine the output. If the result is satisfactory then go to 8. If the result has speed violations then go back to 3. If the result contains catch up problems then, first, go to 5. If the catch up problem cannot be solved by changing grades, then go to 3.

8. Examine if any segment (especially the retarder segment) is excessively long, if so, go to 3. Otherwise the design is complete.

A partial set of sample outputs of the final PROFILE run is presented in Figures 3 through 6. Figure 3 shows the "echo back" input data and the collision related statistics. A comparison of Figure 3 with Figure 2 indicates that in the final run (Figure 3) the master retarder has been eliminated and the track segment between the hump crest and the first switch has been shortened somewhat relative to the initial geometry. The two PROFILE runs presented in Figures 2 and 3 collectively represent an example of the interactive and iterative design procedure presented above. They demonstrate a considerable cost reduction in the design achieved by eliminating the master retarder. The collision related output in Figure 3 indicates that a collision occurred after the clearance point between the hard roller and the easy roller; this is considered to satisfy the problem objectives.

Figure 4 shows a part of the output for Car no. 2 (the easy roller). All the necessary data related to the movements of Car No. 2 is included in this table.

Figure 5 shows a plot of the speeds of cars versus distance. The numbers 1 and 3 in the figure indicate the first and the third car (both hard rollers) and 2 the second car (the easy roller). This figure shows that the easy roller attains a maximum speed of about 24 kph (15 mph); from the more exact output shown in Figure 4, it can be seen that the maximum speed of the easy roller is slightly less than 24 kph (15 mph).

Figure 6 shows a plot of distance headway between successive cars. In this figure the number 2 indicates the headway between Car no. 1 and Car no. 2, and 3 indicates the headway between Car no. 2 and Car no. 3. From Figures 3 and 6 we find that there is sufficient headway between cars to detect individual cars and throw the switch in all switch segments.

Further Work and Concluding Remarks

Further work is in progress to enhance the interactive capability of the program. In particular, consideration is being given to aiding user input procedures, and increasing the amount of graphical output. Also, more work is required to characterize and quantitize the nature of car rollability. Essentially an input to PROFILE, freight car rolling behavior is a critical determinant of the final profile design.

This paper has shown that PROFILE can be used to eliminate the tedious manual process of evaluating hump profile designs using scale drawings. In addition, PROFILE gives a precise prediction of catch-up problems between cars. The utility of the program is to allow the yard designer to evaluate many more design alternatives than previously possible, thus insuring the most cost-effective design.

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