INTRODUCTION

TRANSPORT is a first- and second-order matrix multiplication computer program intended for the design of static-magnetic beam transport systems. It has been in existence in various evolutionary versions since 1963. The present version, described in this manual, includes both first- and second-order fitting capabilities.

Many people from various laboratories around the world have contributed either directly or indirectly to the development of TRANSPORT. The first-order matrix methods were developed by the AGS machine theorists[1] followed by a paper by Penner[2]. The extension of the first-order matrix methods to include second and higher orders was conceived and developed by Brown, Belbeoch and Bounin[3] in Orsay, France, in 1958-59. The original first-order TRANSPORT computer program was written in BALGOL by C.H. Moore at SLAC in collaboration with H.S. Butler and S.K. Howry in 1963. The second-order portion of the program was developed and debugged by Howry and Brown[4], also in BALGOL. The resulting BALGOL version was translated into FORTRAN by S. Kowalski at MIT and later debugged and improved by Kear, Howry and Brown at SLAC[5]. In 1971-72, D. Carey at FNAL completely rewrote the program and developed an efficient second-order fitting routine using the coupling coefficient (partial derivatives) of multipole components to the optics as derived by Brown[6]. This version was implemented at SLAC by F. Rothacker in the early spring of 1972 and subsequently carried to CERN in April, 1972, by K.L. Brown. C. Iselin of CERN made further contributions to the program structure and improved the convergence capabilities of the first-order fitting routines.

A standard version of the resulting program has now been adopted at SLAC, FNAL, and CERN. This manual describes the use of this standard version <u>and is not necessarily applicable to other versions of TRANSPORT</u>. Copies of this manual may be obtained from

1) Scientific Information Service, CERN, 1211 Geneva 23, Switzerland (Ref. CERN 80-04).

2) The Reports Office, Stanford Linear Accelerator Center, P.O. Box 4349, Stanford, CA 94305, USA (Ref. SLAC-91, without the Appendix).

3) The Reports Office, Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510, USA (Ref. NAL-91, "TRANSPORT Appendix" available under separate cover).

The program may be obtained from:

1) IBM Version:

Frank Rothacker
TRANSPORT Program Librarian
Mail Bin 88
Stanford Linear Accelerator Center
P.O. Box 4349
Stanford, CA 94305, USA

2) IBM, CDC or PDP10 Versions:

David C. Carey
Fermi National Accelerator Laboratory
P.O. Box 500
Batavia, IL 60510, USA

3) IBM or CDC Versions:

Program Library
Division DD
CERN
CH 1211 Genève 23
Switzerland

The present authors assume responsibility for the contents of this manual, but in no way imply that they are solely responsible for the entire evolution of the program.

In order to make this report available without delay, the Appendix has been reproduced directly as published by FNAL.

MATHEMATICAL FORMULATION OF "TRANSPORT" *)

General conventions

A beam line is comprised of a set of magnetic elements placed sequentially at intervals along an assumed reference trajectory. The reference trajectory is here taken to be a path of a charged particle passing through idealized magnets (no fringing fields) and having the central design momentum of the beam line.

In TRANSPORT, a beam line is described as a sequence of elements. Such elements may consist not only of magnets and the intervals between them, but also of specifications of the input beam, calculations to be done, or special configurations of the magnets. A certain relation, described below, of the magnets and their fields to the assumed reference trajectory is considered normal. Alternative configurations can be described by means of elements provided for such purposes.

The two coordinates transverse to the initial reference trajectory are labelled as horizontal and vertical. A bending magnet will normally bend in the horizontal plane. To allow for other possibilities a coordinate rotation element is provided. Because of such other possibilities, when describing bending magnets we shall often speak of the bend and non-bend planes. The transverse coordinates will also often be labelled x and y, while the longitudinal coordinate will be labelled z.

All magnets are normally considered "aligned" on the central trajectory. A particle following the central trajectory through a magnet experiences a uniform field which begins and ends abruptly at the entrance and exit faces of the idealized magnet. Therefore, through a bending magnet the reference trajectory is the arc of a circle, while through all other magnetic elements it is a straight line. To accommodate a more gradual variation of field at the ends of a bending magnet a fringing field element is provided. In order to represent an orientation with respect to the reference trajectory other than normal of a magnet or section of a beam line, a misalignment element also exists.

The magnetic field of any magnet, except a solenoid, is assumed to have midplane symmetry. This means that the scalar potential expanded

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*) For a more complete description of the mathematical basis of TRANSPORT, refer to SLAC-75 [4], and to other references listed at the end of this manual.

in transverse coordinates about the reference trajectory is taken to be an odd function of the vertical coordinate. If a coordinate rotation is included, then the potential is odd in the coordinate to which the vertical has been rotated. For a bending magnet this will always be in the non-bend plane.

The program TRANSPORT will step through the beam line, element by element, calculating the properties of the beam or other quantities, described below, where requested. Therefore one of the first elements is a specification of the phase space region occupied by the beam entering the system. Magnets and intervening spaces and other elements then follow in the sequence in which they occur in the beam line. Specifications of calculations to be done or of configurations other than normal are placed in the same sequence, at the point where their effect is to be made.

The transfer matrix R

The following of a charged particle through a system of magnetic lenses may be reduced to a process of matrix multiplication. At any specified position in the system an arbitrary charged particle is represented by a vector (single column matrix) X, whose components are the positions, angles, and momentum of the particle with respect to the reference trajectory, i.e.

$$X = \begin{bmatrix} x \\ \theta \\ y \\ \phi \\ \ell \\ \delta \end{bmatrix}$$

Definitions:

- x = the horizontal displacement of the arbitrary ray with respect to the assumed central trajectory.
- θ = the angle this ray makes in the horizontal plane with respect to the assumed central trajectory.
- y = the vertical displacement of the ray with respect to the assumed central trajectory.
- ϕ = the vertical angle of the ray with respect to the assumed central trajectory.

ℓ = the path length difference between the arbitrary ray and the central trajectory.

δ = $\Delta p/p$ is the fractional momentum deviation of the ray from the assumed central trajectory.

This vector, for a given particle, will henceforth be referred to as a ray. The magnetic lens is represented to first order by a square matrix R, which describes the action of the magnet on the particle coordinates. Thus the passage of a charged particle through the system may be represented by the equation

$$X(1) = RX(0) , \qquad (1)$$

where X(0) is the initial coordinate vector and X(1) is the final coordinate vector of the particle under consideration. The same transformation matrix R is used for all such particles traversing a given magnet [one particle differing from another only by its initial coordinate vector X(0)].

The traversing of several magnets and interspersing drift spaces is described by the same basic equation, but with R now being replaced by the product matrix R(t) = R(n) ... R(3)R(2)R(1) of the individual matrices of the system elements. This cumulative transfer matrix is automatically calculated by the program and is called TRANSFORM 1. It may be printed where desired, as described in later sections.

This formalism may be extended to second order by the addition of another term[4]. The components of the final coordinate vector, in terms of the original, are now given as

$$X_i(1) = \sum_j R_{ij} \, X_j(0) + \sum_{jk} T_{ijk} \, X_j(0) \, X_k(0) ,$$

where T is the second-order transfer matrix. It too is accumulated by the program as one traverses a series of elements. At each point the series is again truncated to second order. Normally the program will calculate only the first-order terms and their effect. If it is desired to include second-order effects in a beam line, an element is provided which specifies that a second-order calculation is to be done. For more information on the T matrix, see the references at the end of the manual.

The following of a charged particle via TRANSPORT through a system of magnets is thus analogous to tracing rays through a system of optical lenses. The difference is that TRANSPORT is a matrix calculation which truncates the problem to either first- or second-order in a Taylor's expansion about a central trajectory. For studying beam optics to greater precision than a second-order TRANSPORT calculation permits, ray-tracing programs which directly integrate the basic differential equation of motion are recommended[7].

The beam matrix σ

In accelerator and beam transport systems, the behaviour of an individual particle is often of less concern than is the behaviour of a bundle of particles (the beam), of which an individual particle is a member. An extension of the matrix algebra of Eq. (1) provides a convenient means for defining and manipulating this beam. TRANSPORT assumes that the beam may be correctly represented in phase space by an ellipsoid in the six-dimensional coordinate system described above. Particles in a beam are assumed to occupy the volume enclosed by the ellipsoid, each point representing a possible ray. The sum total of all phase points, the phase space volume, is commonly referred to as the "phase space" occupied by the beam.

The validity and interpretation of this phase ellipse formalism must be ascertained for each system being designed. However, in general, for charged particle beams in, or emanating from accelerators, the first-order phase ellipse formalism of TRANSPORT is a reasonable representation of physical reality. For other applications, such as charged particle spectrometers, caution is in order in its use and interpretation.

The equation of an n-dimensional ellipsoid may be written in matrix form as follows:

$$X(0)^T \sigma(0)^{-1} X(0) = 1 \, , \qquad (2)$$

where $X(0)^T$ is the transpose of the coordinate vector $X(0)$, and $\sigma(0)$ is a real, positive definite, symmetric matrix.

The volume of the n-dimensional ellipsoid defined by sigma is $[\pi^{n/2}/\Gamma(n/2 + 1)]\,(\det \sigma)^{\frac{1}{2}}$. The area of the projection in one plane is

$A = \pi(\det \sigma_1)^{\frac{1}{2}}$, where σ_1 is the submatrix corresponding to the given plane. This is the "phase space" occupied by the beam.

As a particle passes through a system of magnets, it undergoes the matrix transformation of Eq. (1). Combining this transformation with the equation of the initial ellipsoid, and using the identity $RR^{-1} = I$ (the unity matrix), it follows that

$$X(0)^T(R^T R^{T^{-1}})\sigma(0)^{-1}(R^{-1}R)X(0) = 1$$

from which we derive

$$[RX(0)]^T[R\sigma(0)R^T]^{-1}[RX(0)] = 1 \ . \qquad (3)$$

The equation of the new ellipsoid after the transformation becomes

$$X(1)^T\sigma(1)^{-1}X(1) = 1 \ , \qquad (4)$$

where

$$\sigma(1) = R\sigma(0)R^T \ . \qquad (5)$$

It can readily be shown that the square roots of the diagonal terms of the sigma matrix are a measure of the "beam size" in each coordinate. The off-diagonal terms determine the orientation of the ellipsoid in n-dimensional space (for TRANSPORT n = 6)*). Thus, we may specify the beam at any point in the system via Eq. (5), given the initial "phase space" represented by the matrix elements of $\sigma(0)$.

The initial beam is specified by the user as one of the first elements of the beam line. Normally it is taken to be an upright ellipse centred on the reference trajectory; that is, there are no correlations between coordinates. Both correlations and centroid displacements may be introduced via additional elements.

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*) See the Appendix of this report, or the Appendix of Ref. 5, for a derivation of these statements.

The phase ellipse may be printed wherever desired. For an interpretation of the parameters printed see the section under type code 1.0.

When a second-order calculation is specified the second-order matrix elements are included in the beam matrix. For details on how this is done see the Appendix to this manual.

Fitting

Several types of physical elements have been incorporated in the program to facilitate the design of very general beam transport systems. Included are an arbitrary drift distance, bending magnets, quadrupoles, sextupoles, solenoids, and an accelerator section (to first-order only). Provision is made in the program to vary some of the physical parameters of the elements comprising the system and to impose various constraints on the beam design. In a first-order run one may fit either the TRANSFORM (R) matrix representing the transformation of an arbitrary ray through the system and/or the phase ellipse (sigma) matrix representing a bundle of rays by the system as transformed. In a second-order run one may fit either the second-order TRANSFORM (T) matrix or minimize the net contribution of second-order terms to the beam (sigma) matrix.

The program will normally make a run through the beam line using values for the physical parameters as specified by the user and printing the results. If constraints and parameters to be varied are indicated, it will attempt to fit. To do this it will make an additional series of runs through the beam line. Each time it will calculate corrections to be made from the previous step to the varied parameters to try to satisfy the indicated constraints. When the constraints are satisfied (or the fitting procedure has failed) the program will make a final run through the beam line again printing the results. In this final run the values of the physical parameters used are those which are the result of the fitting procedure.

Thus, in principle, the program is capable of searching for and finding the first- or second-order solution to any physically realizable problem. In practice, life is not quite so simple. The user will find that an adequate knowledge of geometric magnetic optics principles is a necessary prerequisite to the successful use of TRANSPORT. He (or she) should possess a thorough understanding of the first-order matrix algebra of beam transport optics and of the physical interpretation of the various matrix elements.

In other words, the program is superb at doing the numerical calculations for the problem but not the physics. The user must provide a reasonable physical input if he (or she) expects complete satisfaction from the program. For this reason a list of pertinent reprints and references are included at the end of this manual. They should provide assistance to the inexperienced as well as the experienced user.

INPUT FORMAT FOR TRANSPORT

By the TRANSPORT input DATA SET is meant the totality of data read by the program in a single job. A DATA SET may consist of one or more problems placed sequentially. A problem specifies a calculation or set of calculations to be done on a given beam line.

A problem, in turn, may consist of one or more problem steps. The data in the first step of a problem specify the beam line and the calculations to be made. The data in succeeding steps of the same problem specify only changes to the data given in the first step.

A common example of a problem with several steps is sequential fitting. In the first step one may specify that certain parameters are to be varied to satisfy certain constraints. Once the desired fit has been achieved the program will then proceed to the next step. The data in this step now need specify only which new parameters to vary, or old ones no longer to vary, or which constraints to add or delete. The values of the varied parameters that are passed from one step to the next one are those that are the result of the fitting procedure.

A problem step contains three kinds of DATA cards: the TITLE card, the INDICATOR card, and the ELEMENT cards.

The TITLE card contains a string of characters and blanks enclosed by single quotes. Whatever is between the quotes will be used as a heading in the output of a TRANSPORT run.

The second card of the input is the INDICATOR card. If the data which follow describe a new problem, a zero (0) is punched in any column on the card. If the data which follow describe changes to be made in the previous problem step, a one (1) or two (2) is punched in any column on the card. For further explanation read the Indicator Card section of this manual.

The remaining cards in the deck for a given problem step contain the DATA describing the beam line and the calculations to be done. The DATA consist of a sequence of elements whose order is the same as encountered as one proceeds down the beam line. Each element specifies a magnet or portion thereof or other piece of equipment, a drift space, the initial beam phase space, a calculation to be done, or a print instruction. Calculation specifications, such as misalignments and constraints, are placed in sequence with the other beam line elements where their effect is to take place. The input format of the cards is "free-field", which is described below. The data for a given problem step are terminated by the word SENTINEL, which need not be punched on a separate card.

Each element, in turn, is given by a sequence of items (mostly numbers), separated by spaces and terminated by a semicolon. The items, in order, are a type code number, a vary field, the physical parameters, and an optional label.

The type code number identifies the element, indicating what sort of entity (such as a magnet, drift space, constraint, etc.) is represented. It is an integer (number) followed by a decimal point. The interpretation of the physical parameters which follow is therefore dependent on the type code number. The type code numbers and their meanings are summarized in Table 1. If the type code number is negative, the element will be ignored in the given problem step. However, storage for that element will be allocated by the program, so that the element may be introduced in a later step of the same problem. Storage space for any element in any problem step must be allocated in the first step of the problem.

The vary field indicates which physical parameters of the element are to be adjusted if there is to be any fitting. It is punched immediately (no intervening blanks) to the right of the decimal point of the type code number. See the section under type code 10.0 for an explanation of the use of vary codes.

The physical parameters are the quantities which describe the physical element represented. Such parameters may be lengths, magnetic fields, apertures, rotation angles, beam dimensions, or other quantities, depending on the type code number. The meanings for the physical parameters for each type code are described thoroughly in the section for that type code. A summary, indicating the order in which the physical parameters should be punched, is given in Table 1. For any element the first physical parameter is the second entry in Table 1 or the second parameter in the section describing a given element. In some cases the parameters of an element do not really refer to physical quantities, but will nevertheless be referred to as such in this manual.

The label, if present, contains one to four characters and is enclosed by single quotes, slashes or equal signs. During the calculation the elements will be printed in sequence and the label for a given element will be printed with that element. Labels are useful in problems with many elements and/or when sequential fitting is used. They must be used to identify any element to be changed in succeeding steps of a given problem.

Provision has been made in the program to allow the user to introduce comments before any type code entry in the data deck. This is accomplished by enclosing the comments made on each card within single parentheses.

Each element must be terminated by a semicolon (;). Optionally a semicolon may be replaced by an asterisk (*) or a dollar sign ($). Spaces before and after the semicolon are allowed but not required. If the program encounters a semicolon, dollar sign or asterisk before the expected number of parameters has been read in and if the indicator card was a zero (0), the remaining parameters are set to zero. If the indicator card was a one (1) or two (2), then the numbers indicated on the card are substituted for the numbers remaining from the previous solution; all other numbers are unchanged.

The "free-field" input format of the data cards makes it considerably easier to prepare input than the standard fixed-field formats of FORTRAN. Numbers may be punched anywhere on the card and must simply be in the proper order. They must be separated by one or more blanks. Several elements may be included on the same card and a single element may continue from one card to the next. A single number must be all on one card, it may not continue from one card to the next. The program storage is limited to a total of 2000 locations (including type codes and those parameters not punched but implied equal to zero) and 500 elements.

A decimal number (e.g. 2.47) may be represented in any of the following ways:

```
2.47
.00247+3
.0247E+02
247E-2
247000-5
```

The sample problem below contains two problem steps, each beginning with title and indicator cards and terminating with a SENTINEL. The first step causes TRANSPORT to do a first-order calculation with fitting. The second initiates a second-order calculation with the data that is a result of that fitting. Corresponding elements between the two steps are identified by having the same label.

The type ten element which specifies the fitting condition is labelled FIT1. It is active for the first-order calculation, but is turned off for the second-order calculation. The vary codes for elements DR1 are set to zero for the second-order problem. The second-order element, SEC1, is ineffective during the fitting, but causes the program to compute the second-order matrices in the second calculation.

An Example of a TRANSPORT Input Deck

'FORTRAN H CHECK ON BETA FIT'	*Title card*	
0	*Indicator card*	
1 .5 1 .5 1 .5 1 1 ;		
-17 'SEC1' ; 13 3 ;		
3.3 2.745 'DR1' ;		*First problem step*
2 0 ; 4 9.879 10 .5 ; 2 0 ;	*Elements*	
3.3 2.745 'DR1' ;		
13 4 ;		
10 -1 2 0 .0001 'FIT1' ;		
SENTINEL		
'SECOND ORDER'	*Title card*	
1	*Indicator card*	
17 'SEC1' ;		*Second problem step*
3 'DR1' ;	*Elements to be changed*	
-10 'FIT1' ;		
SENTINEL		
SENTINEL	*Second sentinel signifies end of run.*	

As many problems and problem steps as one wishes may be stacked in one job.

Note that in previous versions of TRANSPORT a decimal point was required with every numerical entry except the indicator card (which must not have a decimal point in any version of TRANSPORT).

The use of labels

The use of labels is available for identification of individual elements. When inserted for the user's convenience, the association of a label with a given element is optional. If the parameters of an element are to be changed between steps of a given problem, a label is required. The label identifies the element in the earlier step to which the changes specified in the later step are to apply.

The label may be placed anywhere among the parameters of a given element. It should be enclosed in quotes, slashes, or equal signs. Blanks within a label are ignored. The maximum length of a label is four non-blank characters.

As an example, the following all denote the same drift space:

```
'DRF'     3.     1.5     ;
3/DRF/15-1*
3.      .15E1     = D R F =     $
```

On a 15.0 type code element the label may not be the third item. This is to avoid ambiguities with the unit name. Thus the following are not equivalent:

This entry is used as the units symbol.

This entry is used as a label.

```
15.     1.     'FT'     'CM'     ;
15.     1.     'CM'     'FT'     ;
```

If the parameters describing an element are to differ in succeeding steps of a given problem the element must be included in both steps, having the same label each time. All elements which appear in a problem must be included in the first step (indicator card 0) of that problem. Only those to be changed in later steps need to be labelled. In later steps (indicator card 1) of a problem only those elements to be changed are specified. The elements to be changed are identified by their labels.

If the type code number of an element is negative in a given step of a problem, that element will be ignored when the calculation is performed. However, storage space in the computer will be allocated for the element for possible activation in later steps of the problem. In the later step, only those parameters to be changed need to be specified.

The storage space allocated for the parameters of a given element is determined only by the type code. The sole exceptions are the continuation codes for type codes 1.0 and 14.0.

For example, if a fitting constraint is to be ignored in the first step of a problem, but activated in a later step, it should be indicated in both steps. In the first step such an element might appear as

```
-10.   'FIT'   ;
```

In the later step one would then insert

```
10.   1.   2.   0.0   .001   'FIT'   ;
```

causing a waist constraint to be imposed on the beam. Alternatively one can specify the physical parameters in the first step and then, in the later step, merely indicate that the element is now to be activated. The above procedure is therefore equivalent to placing the element:

```
-10.   1.   2.   0.0   .001   'FIT'   ;
```

in the first problem step, and the element

```
10.   'FIT'   ;
```

in the later step.

Vary codes may also be inserted or removed in passing from one problem step to the next. For instance, one might wish to vary the field of a quadrupole in one step of a problem and then use the fitted value as data in the following step. The first step might then contain the element:

```
5.01   5.0   10.0   5.0   'QUAD'   ;
```

and the following step would contain the element

```
5.   'QUAD'   ;
```

Since, in the second step, the first item on the card contains no vary code the vary code is deleted. All other parameters, not being re-specified, are left unchanged.

Several elements may have the same label. If, as in the above example, one wished to vary the field of several quadrupoles in one step, then pass the final values to the next step, one could give all such elements the same label. There might be four quadrupoles, all labelled 'QUAD', being varied simultaneously. If the data for the next step contain the single element

```
5.    'QUAD'    ;
```

the vary code on all elements labelled 'QUAD' will be deleted.

The physical parameters of an element may be changed between steps of a problem. In the first step a bending magnet may be given a length of 5 metres.

```
4.    5.0    10.0    0.0    'BEND'    ;
```

In a succeeding step, its length could be increased to 10 metres by inserting the element

```
4.    10.0    'BEND'    ;
```

All parameters, up to and including the one to be changed, must be specified. The remaining, if omitted, will be left unchanged from the previous step.

Table 1: Summary of TRANSPORT type codes

PHYSICAL ELEMENT	TYPE CODE	2nd ENTRY	3rd ENTRY	4th ENTRY	5th ENTRY	6th ENTRY	7th ENTRY	8th ENTRY	9th ENTRY
BEAM	1.vvvvvv0	x(cm)	θ(mr)	y(cm)	ϕ(mr)	ℓ(cm)	δ(percent)	p_0	
r.m.s. ADDITION TO BEAM ENVELOPE	1.vvvvvv00	Δx(cm)	$\Delta\theta$(mr)	Δy(cm)	$\Delta\phi$(mr)	$\Delta\ell$(cm)	$\Delta\delta$(percent)	ΔP (GeV/c)	0
POLE FACE ROTATION	2.v	ANGLE OF ROTATION (degrees)							
DRIFT	3.v	LENGTH (metres)							
BENDING MAGNET	4.vvv	LENGTH (metres)	FIELD (kG)	FIELD GRADIENT (n-value)					
QUADRUPOLE	5.vv0	LENGTH (metres)	FIELD (kG)	HALF-APERTURE (cm)					
TRANSFORM 1 UPDATE	6.0	0.0	1.0						
TRANSFORM 2 UPDATE	6.0	0.0	2.0						
BEAM CENTROID SHIFT	7.0	SHIFT (x)(cm)	SHIFT (θ) (mr)	SHIFT (y)(cm)	SHIFT (ϕ)(mr)	SHIFT (ℓ)(cm)	SHIFT (δ percent)		
ALIGNMENT TOLERANCE	8.vvvvvv0	DISPLACEMENT (x)(cm)	ROTATION (θ)(mr)	DISPLACEMENT (y)(cm)	ROTATION (ϕ)(mr)	DISPLACEMENT (z)(cm)	ROTATION (α)(mr)	CODE NUMBER	
REPEAT CONTROL	9.0	NUMBER OF REPEATS							
FITTING CONSTRAINTS	10.0	±I	J	DESIRED VALUE OF (I,J) MATRIX ELEMENTS	ACCURACY OF FIT				
Note: +I is used for fitting a beam (σ) matrix element. -I is used for fitting an R1 matrix element. - (I + 20) is used for fitting an R2 matrix element.									
ACCELERATOR	11.0	LENGTH (metres)	E (energy gain) (GeV)	ϕ (phase lag) (degrees)	(WAVELENGTH) (cm)				
BEAM (Rotated Ellipse)	12.0	THE FIFTEEN CORRELATIONS AMONG THE SIX ELEMENTS (This entry must be preceded by a type code 1.0 entry.)							
INPUT/OUTPUT OPTIONS	13.0	CONTROL CODE NUMBER							
ARBITRARY R MATRIX	14.vvvvvv0	R(J,1)	R(J,2)	R(J,3)	R(J,4)	R(J,5)	R(J,6)	J	
UNITS CONTROL (Transport Dimensions)	15.0	CODE	UNIT SYMBOL	SCALE FACTOR (if required)					
QUADRATIC TERM OF BENDING FIELD	16.0v	1.0	$\epsilon(1) = B(\frac{1}{\rho_0})^2$	ρ_0 in units of transverse length (cm)					
MASS OF PARTICLES IN BEAM	16.0	3.0	M/m (dimensionless)	m = mass of electron					
HALF-APERTURE OF BENDING MAGNET IN x-PLANE	16.0	4.0	w/2 (cm)						
HALF-APERTURE OF BENDING MAGNET IN y-PLANE (gap)	16.0	5.0	g/2 (cm)						
LENGTH OF SYSTEM	16.0	6.0	L (metres)						
FRINGE FIELD CORRECTION COEFFICIENT	16.0	7.0	K_1 (dimensionless)						
FRINGE FIELD CORRECTION COEFFICIENT	16.0	8.0	K_2 (dimensionless)						
CURVATURE OF ENTRANCE FACE OF BENDING MAGNET	16.0v	12.0	$(1/R_1)$ (1/metres)						
CURVATURE OF EXIT FACE OF BENDING MAGNET	16.0v	13.0	$(1/R_2)$ (1/metres)						
FOCAL PLANE ROTATION	16.0	15.0	Angle of focal plane rotation (degrees). See type code 16.0 for details.						
INITIAL BEAM LINE x-COORDINATE	16.0	16.0	x_0						
INITIAL BEAM LINE y-COORDINATE	16.0	17.0	y_0						
INITIAL BEAM LINE z-COORDINATE	16.0	18.0	z_0						
INITIAL BEAM LINE HORIZONTAL ANGLE	16.0	19.0	θ_0						
INITIAL BEAM LINE VERTICAL ANGLE	16.0	20.0	ϕ_0						
SECOND-ORDER CALCULATIONS	17.0								
SEXTUPOLE	18.0v	LENGTH (metres)	FIELD (kG)	HALF-APERTURE (cm)					
SOLENOID	19.vv	LENGTH (metres)	FIELD (kG)						
BEAM ROTATION	20.v	ANGLE OF ROTATION (degrees)							
STRAY FIELD	21.0	See later section of report.							

Note: The v's following the type codes indicate the parameters which may be varied. See section under type code 10.0 for a detailed explanation of Vary Codes. The units are standard TRANSPORT units (as shown) unless changed via type code 15.0 entries.

OUTPUT FORMAT

General appearance

Here we give a brief description of the general appearance of the output and its meaning. The user may refer to the sample output shown on pages 22 through 27. It is the printed output resulting from the sample data shown in the section on input format. In a simple example it is not possible to show each of the different type codes. Several of the type codes produce output which is not characteristic of all other type codes. We therefore refer the user to the sections on the various type codes for an explanation of any features peculiar to a given type code.

The output for each step of a given problem is printed separately. The printing for one step is completed before that for the next step is begun. Therefore we will describe the output for a single problem step. The output shown below is from a problem with two steps.

Initial listing

For each problem step, the program begins by printing out the user's input records.

Listing during the calculation

The program now begins the calculation. If there is no fitting, one listing of the beam line will be made. If there is fitting there will normally be two listings. The first will represent the beam line before any fitting has occurred. The second will be based on the new values of the physical parameters which were altered by the fitting process. If sequential fitting is employed and an indicator card of two (2) is used the first run will be omitted. The user should read the section describing the indicator card for further explanation.

In any listing the elements are printed in order with their labels and physical parameters. Elements with negative type code numbers are ignored. Each listed element is preceded by the name of that type of element, enclosed in asterisks. All physical elements are listed in this way. Some of the other elements are not explicitly listed but produce their effect in either the calculated quantities or the listing of the beam line. For descriptions of individual cases, the reader should consult the sections on the type codes.

Calculated quantities appear in the listing as requested in the input data. Important cases will be described in greater detail below. The physical parameters for each element are printed with the appropriate units. For some elements a calculated quantity, not in the input data, will appear, enclosed in parenthesis. Such quantities are explained in the sections under the individual type codes.

Calculated quantities

The important cases of calculated quantities which appear in the output are the transfer matrices, the beam matrix, the layout coordinates, and the results of the fitting procedure. The transfer and beam matrices and layout coordinates appear as requested in the listing of the beam line. The results of the fitting procedure appear between the two listings. All these quantities are explained in greater detail below.

The transfer and beam matrices appear only where requested. A request for printing of layout coordinates should be made at the beginning of the beam line. The coordinates will then be printed after each physical element. In all cases the quantities printed are the values at the interface between two elements. They are evaluated at a point after the element listed above them and before the element listed below. For further explanation of calculated quantities the user should read the section on the mathematical formulation of TRANSPORT, the appendix to the manual, and the section on the appropriate type code. For the transfer matrix the appropriate type code is thirteen; for the beam matrix it is one, and for the coordinate layout it is again thirteen.

Quantities relevant to the fitting appear between the two listings of the beam line. At each iteration of the fitting procedure a line is printed containing the value of the relaxation factor used, the value of chi-squared before the iteration was made, and the corrections made to each of the varied parameters. Once the fitting is complete the final chi-squared and the covariance matrix are printed. For further details the user should read the section on type code 10.0, and the section on fitting in the appendix.

```
*FORTRAN H CHECK ON BETA FIT *

    0
    1.000000                .50000    1.00000    .50000    1.00000    .50000    1.00000    1.00000;
  -17.        *SECI* ;
   13.                     3.00000;
    3.3       *DRI *       2.74500;
    2.0                    0.00000;
    4.000                  9.87900   10.00000    .50000;
    2.0                    0.00000;
    3.3       *DRI *       2.74500;
   13.                     4.00000;
   10.0       *FITI*      -1.00000    2.00000    0.00000    .00010;

SENTINEL
```

```
FORTRAN H CHECK ON BETA FIT

*BEAM*          1.              1.00000 GEV
    0.000 M                                                      0.000    .500 CM
                                                                 0.000   1.000 MR     0.000
                                                                 0.000    .500 CM     0.000  0.000
                                                                 0.000   1.000 MR     0.000  0.000  0.000
                                                                 0.000    .500 CM     0.000  0.000  0.000  0.000
                                                                 0.000   1.000 PC     0.000  0.000  0.000  0.000  0.000
*DRIFT*         3.   "DRI "     2.74500 M
   VARY CODE =  3
    2.745 M                                                      0.000    .570 CM
                                                                 0.000   1.000 MR      .481
                                                                 0.000    .570 CM     0.000  0.000
                                                                 0.000   1.000 MR     0.000  0.000   .481
                                                                 0.000    .500 CM     0.000  0.000  0.000  0.000
                                                                 0.000   1.000 PC     0.000  0.000  0.000  0.000  0.000
*ROTAT*         2.              0.00000 DEG
    2.745 M                                                      0.000    .570 CM
                                                                 0.000   1.000 MR      .481
                                                                 0.000    .570 CM     0.000  0.000
                                                                 0.000   1.000 MR     0.000  0.000   .481
                                                                 0.000    .500 CM     0.000  0.000  0.000  0.000
                                                                 0.000   1.000 PC     0.000  0.000  0.000  0.000  0.000
*BEND*          4.              9.87900 M        10.00000 KG    .50000    (     3.336 M  , 169.690 DEG )
   12.624 M                                                      0.000  10.013 CM
                                                                 0.000  12.324 MR      .993
                                                                 0.000    .369 CM     0.000  0.000
                                                                 0.000   1.360 MR     0.000  0.000  -.086
                                                                 0.000  11.690 CM     -.992  -.972  0.000  0.000
                                                                 0.000   1.000 PC      .999   .994  0.000  0.000  -.991
*ROTAT*         2.              0.00000 DEG
   12.624 M                                                      0.000  10.013 CM
                                                                 0.000  12.324 MR      .993
                                                                 0.000    .369 CM     0.000  0.000
                                                                 0.000   1.360 MR     0.000  0.000  -.086
                                                                 0.000  11.690 CM     -.992  -.972  0.000  0.000
                                                                 0.000   1.000 PC      .999   .994  0.000  0.000  -.991
*DRIFT*         3.   "DRI "     2.74500 M
   VARY CODE =  3
   15.369 M                                                      0.000  13.378 CM
                                                                 0.000  12.324 MR      .996
                                                                 0.000    .502 CM     0.000  0.000
                                                                 0.000   1.360 MR     0.000  0.000   .681
                                                                 0.000  11.690 CM     -.988  -.972  0.000  0.000
                                                                 0.000   1.000 PC      .999   .994  0.000  0.000  -.991
*TRANSFORM 1*
          -1.00383   -.00418   0.00000   0.00000   0.00000  13.36811
          -1.83605  -1.00383   0.00000   0.00000   0.00000  12.24881
           0.00000   0.00000  -1.00383   -.00418   0.00000   0.00000
           0.00000   0.00000  -1.83605  -1.00383   0.00000   0.00000
          -1.22488  -1.33681   0.00000   0.00000   1.00000 -11.58647
           0.00000   0.00000   0.00000   0.00000   0.00000   1.00000
*FIT*        10.0  "FIT1"     -1.   2.      0.00000 / .00010       (    -.00418 )

*LENGTH*         15.36900 M

*CORRECTIONS*
  .10000E+01 (   .17464E+04)     -.0208
  .10000E+01 (   .63283E-02)     -.0000

*COVARIANCE  (FIT  .84364E-13 )
       .000
```

```
FORTRAN H CHECK ON BETA FIT

*BEAM*        1.              1.00000 GEV
    0.000 M                                                                0.000    .500 CM
                                                                           0.000   1.000 MR    0.000
                                                                           0.000    .500 CM    0.000  0.000
                                                                           0.000   1.000 MR    0.000  0.000  0.000
                                                                           0.000    .500 CM    0.000  0.000  0.000  0.000
                                                                           0.000   1.000 PC    0.000  0.000  0.000  0.000  0.000
*DRIFT*       3.   "DRI "     2.72415 M
   VARY CODE =  3
    2.724 M                                                                0.000    .569 CM
                                                                           0.000   1.000 MR     .478
                                                                           0.000    .569 CM    0.000  0.000
                                                                           0.000   1.000 MR    0.000  0.000   .478
                                                                           0.000    .500 CM    0.000  0.000  0.000  0.000
                                                                           0.000   1.000 PC    0.000  0.000  0.000  0.000  0.000
*ROTAT*       2.              0.00000 DEG
    2.724 M                                                                0.000    .569 CM
                                                                           0.000   1.000 MR     .478
                                                                           0.000    .569 CM    0.000  0.000
                                                                           0.000   1.000 MR    0.000  0.000   .478
                                                                           0.000    .500 CM    0.000  0.000  0.000  0.000
                                                                           0.000   1.000 PC    0.000  0.000  0.000  0.000  0.000
*BEND*        4.              9.87900 M        10.00000 KG        .50000   (     3.336 M    , 169.690 DEG )
   12.603 M                                                                0.000  10.013 CM
                                                                           0.000  12.324 MR     .993
                                                                           0.000    .370 CM    0.000  0.000
                                                                           0.000   1.357 MR    0.000  0.000  -.086
                                                                           0.000  11.690 CM    -.992  -.972  0.000  0.000
                                                                           0.000   1.000 PC     .999   .994  0.000  0.000  -.991
*ROTAT*       2.              0.00000 DEG
   12.603 M                                                                0.000  10.013 CM
                                                                           0.000  12.324 MR     .993
                                                                           0.000    .370 CM    0.000  0.000
                                                                           0.000   1.357 MR    0.000  0.000  -.086
                                                                           0.000  11.690 CM    -.992  -.972  0.000  0.000
                                                                           0.000   1.000 PC     .999   .994  0.000  0.000  -.991
*DRIFT*       3.   "DRI "     2.72415 M
   VARY CODE =  3
   15.327 M                                                                0.000  13.352 CM
                                                                           0.000  12.324 MR     .996
                                                                           0.000    .500 CM    0.000  0.000
                                                                           0.000   1.357 MR    0.000  0.000   .676
                                                                           0.000  11.690 CM    -.989  -.972  0.000  0.000
                                                                           0.000   1.000 PC     .999   .994  0.000  0.000  -.991
*TRANSFORM 1*
           -1.00000   -.00000   0.00000   0.00000   0.00000  13.34256
           -1.83605  -1.00000   0.00000   0.00000   0.00000  12.24881
            0.00000   0.00000  -1.00000   -.00000   0.00000   0.00000
            0.00000   0.00000  -1.83605  -1.00000   0.00000   0.00000
           -1.22488  -1.33426   0.00000   0.00000   1.00000 -11.58647
            0.00000   0.00000   0.00000   0.00000   0.00000   1.00000
*FIT*       10.0  "FIT1"     -1.   2.      0.00000 / .00010        (    -.00000 )

*LENGTH*       15.32729 M
```

```
"SECOND ORDER"

    1
   17.             "SECI" ;
    3.0            "DRI " ;
  -10.             "FITI" ;


"SECOND ORDER"

    1
    1.000000                .50000    1.00000     .50000    1.00000     .50000    1.00000    1.00000;
*  17.             "SECI" ;
   13.                     3.00000;
*   3.0            "DRI "  2.72415;
    2.0                    0.00000;
    4.000                  9.87900   10.00000     .50000;
    2.0                    0.00000;
*   3.0            "DRI "  2.72415;
   13.                     4.00000;
* -10.             "FITI" -1.00000    2.00000    0.00000     .00010;

SENTINEL
```

```
SECOND ORDER

*BEAM*          1.                  1.00000 GEV
    0.000 M
                                                                    0.000      .500 CM
                                                                    0.000     1.000 MR     0.000
                                                                    0.000      .500 CM     0.000  0.000
                                                                    0.000     1.000 MR     0.000  0.000  0.000
                                                                    0.000      .500 CM     0.000  0.000  0.000  0.000
                                                                    0.000     1.000 PC     0.000  0.000  0.000  0.000  0.000
*2ND ORDER*    17.    "SEC1"          GAUSSIAN DISTRIBUTION
*DRIFT*         3.    "DRI "        2.72415 M
    2.724 M
                                                                    0.000      .569 CM
                                                                    0.000     1.000 MR     .478
                                                                    0.000      .569 CM     0.000  0.000
                                                                    0.000     1.000 MR     0.000  0.000   .478
                                                                    -.000      .500 CM     0.000  0.000  0.000  0.000
                                                                    0.000     1.000 PC     0.000  0.000  0.000  0.000  0.000
*ROTAT*         2.                  0.00000 DEG
    2.724 M
                                                                     .000      .569 CM
                                                                    0.000     1.000 MR     .478
                                                                    0.000      .569 CM     0.000  0.000
                                                                    0.000     1.000 MR     0.000  0.000   .478
                                                                    -.000      .500 CM     -.000  0.000  0.000  0.000
                                                                    0.000     1.000 PC     0.000  0.000  0.000  0.000  0.000
*BEND*          4.                  9.87900 M          10.00000 KG      .50000   (     3.336 M   , 169.690 DEG )
   12.603 M
                                                                     .068    10.013 CM
                                                                     .037    12.324 MR     .993
                                                                    0.000      .370 CM     0.000  0.000
                                                                    0.000     1.358 MR     0.000  0.000  -.086
                                                                    -.002    11.690 CM     -.992  -.972  0.000  0.000
                                                                    0.000     1.000 PC      .999   .994  0.000  0.000  -.991
*ROTAT*         2.                  0.00000 DEG
   12.603 M
                                                                     .068    10.013 CM
                                                                     .037    12.324 MR     .993
                                                                    0.000      .370 CM     0.000  0.000
                                                                    0.000     1.358 MR     0.000  0.000  -.086
                                                                    -.002    11.690 CM     -.992  -.972  0.000  0.000
                                                                    0.000     1.000 PC      .999   .994  0.000  0.000  -.991
*DRIFT*         3.    "DRI "        2.72415 M
   15.327 M
                                                                     .078    13.352 CM
                                                                     .037    12.324 MR     .996
                                                                    0.000      .500 CM     0.000  0.000
                                                                    0.000     1.358 MR     0.000  0.000   .676
                                                                    -.023    11.690 CM     -.988  -.972  0.000  0.000
                                                                    0.000     1.000 PC      .999   .994  0.000  0.000  -.991
```

```
*TRANSFORM 1*
            -1.00000   -.00000   0.00000   0.00000   0.00000  13.34256
            -1.83605  -1.00000   0.00000   0.00000   0.00000  12.24881
             0.00000   0.00000  -1.00000   -.00000   0.00000   0.00000
             0.00000   0.00000  -1.83605  -1.00000   0.00000   0.00000
            -1.22488  -1.33426   0.00000   0.00000   1.00000 -11.58647
             0.00000   0.00000   0.00000   0.00000   0.00000   1.00000

*2ND ORDER TRANSFORM*
 1 11  1.124E-03
 1 12  1.225E-03   1 22  6.673E-04
 1 13  0.          1 23  0.          1 33 -4.871E-03
 1 14  0.          1 24  0.          1 34 -2.042E-03   1 44 -1.112E-03
 1 15  0.          1 25  0.          1 35  0.          1 45  0.          1 55  0.
 1 16  2.065E-02   1 26  3.066E-02   1 36  0.          1 46  0.          1 56  0.          1 66  7.908E-02

 2 11  6.119E-07
 2 12  1.333E-06   2 22  6.126E-04
 2 13  0.          2 23  0.          2 33 -5.504E-03
 2 14  0.          2 24  0.          2 34 -2.999E-03   2 44 -1.021E-03
 2 15  0.          2 25  0.          2 35  0.          2 45  0.          2 55  0.
 2 16  3.097E-02   2 26  3.564E-02   2 36  0.          2 46  0.          2 56  0.          2 66  3.834E-02

 3 11  0.
 3 12  0.          3 22  0.
 3 13 -7.500E-04   3 23 -2.042E-03   3 33  0.
 3 14 -2.042E-03   3 24 -2.224E-03   3 34  0.          3 44  0.
 3 15  0.          3 25  0.          3 35  0.          3 45  0.          3 55  0.
 3 16  0.          3 26  0.          3 36 -1.064E-02   3 46 -3.414E-03   3 56  0.          3 66  0.

 4 11  0.
 4 12  0.          4 22  0.
 4 13  5.503E-03   4 23  5.994E-03   4 33  0.
 4 14 -2.999E-03   4 24 -2.042E-03   4 34  0.          4 44  0.
 4 15  0.          4 25  0.          4 35  0.          4 45  0.          4 55  0.
 4 16  0.          4 26  0.          4 36  5.756E-03   4 46  4.367E-03   4 56  0.          4 66  0.

*LENGTH*        15.32729 M
```

TITLE CARD

The title card is the first card in every problem step of a TRANSPORT data set. The title card is always required and must be followed by a 0, a 1 or a 2 card (see next section) to indicate whether the data to follow is new (0 card) or a continuation of a previous data set (a 1 card or a 2 card).

The title must be enclosed within either quotation marks ('), slashes (/), or equal signs (=) on a single card. The string may begin and end in any column (free field format), for example

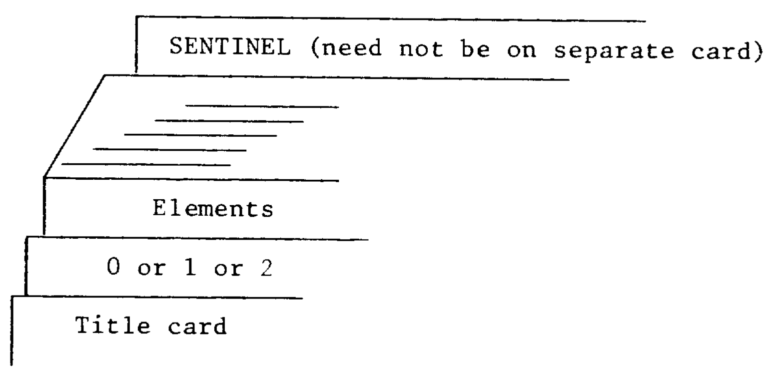
'SLAC 20 GEV/C SPECTROMETER'

or

/SLAC 20 GEV SPECTROMETER/

Note that whichever character is used to enclose the title must not be used again within the title itself.

Example of a DATA SET for a single problem step



INDICATOR CARD

The second card of the input for each step of a problem is the indicator card. If the data which follow describe a new problem, a zero (0) is punched in any column on the card. If the data which follow describe changes to be made in the previous step of a given problem, a one (1) or two (2) is punched in any column on the card.

If a given problem step involves fitting, the program will normally list the beam line twice, printing each time the sequence of elements along with transfer or beam matrices where specified. The first listing uses the parameters of each element before any fitting has taken place. The second shows the results of the fitting. If a problem involving fitting has several steps, the second run of a given step often differs little from the first run of the following step.

If the second or subsequent step of a problem involves fitting and one wishes to print both runs through the beam line, a one (1) is punched on the indicator card. If the first listing is to be suppressed a two (2) is punched. If no fitting is involved, the program will ignore the two and will do one single run through the system.

If the initial listing is to be deleted, 10 is added to the indicator to give 10, 11, or 12. In order to be consistent with earlier versions of TRANSPORT, an indicator of minus one (-1) is interpreted as a two (2), but nine (9) is not interpreted as twelve (12).

The sample problem input shown on page 14 causes TRANSPORT to do a first-order calculation with fitting (0 indicator card) and then to do a second-order calculation (1 indicator card) with the data that is the result of the fitting.

COMMENT CARDS

Comment cards may be introduced anywhere in the deck where an element would be allowed by enclosing the comments made on each card within single parentheses. No parentheses are allowed within the parentheses of any comment card. The comments are not stored, but appear only in the initial listing of the given problem step.

Example of the use of comment cards in a data set

```
'Title Card'
0
(THIS IS A TEST PROBLEM TO ILLUSTRATE THE)
(USE OF COMMENT CARDS)
elements
(COMMENTS MAY ALSO BE MADE BETWEEN)
(TYPE CODE ENTRIES)
elements
SENTINEL
```