

UNCLASSIFIED

AD 278 262

*Reproduced
by the*

**ARMED SERVICES TECHNICAL INFORMATION AGENCY
ARLINGTON HALL STATION
ARLINGTON 12, VIRGINIA**



UNCLASSIFIED

NOTICE: When government or other drawings, specifications or other data are used for any purpose other than in connection with a definitely related government procurement operation, the U. S. Government thereby incurs no responsibility, nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use or sell any patented invention that may in any way be related thereto.

278 262

278262

MEMORANDUM
RM-3207-PR
JULY 1962

CATALOGED BY ASTIA
AS AD NO. _____

ON CONTROL PROBLEMS
WITH BOUNDED STATE VARIABLES

L. D. Berkovitz

ASTIA
JUL 23 1962
TISIA A

PREPARED FOR:
UNITED STATES AIR FORCE PROJECT RAND

The RAND Corporation
SANTA MONICA • CALIFORNIA

MEMORANDUM

RM-3207-PR

JULY 1962

ON CONTROL PROBLEMS
WITH BOUNDED STATE VARIABLES

L. D. Berkovitz

This research is sponsored by the United States Air Force under Project RAND — Contract No. AF 49(638)-700 — monitored by the Directorate of Development Planning, Deputy Chief of Staff, Research and Technology, Hq USAF. Views or conclusions contained in this Memorandum should not be interpreted as representing the official opinion or policy of the United States Air Force. Permission to quote from or reproduce portions of this Memorandum must be obtained from The RAND Corporation.

The RAND Corporation

1700 MAIN ST • SANTA MONICA • CALIFORNIA

PREFACE

The Memorandum is part of the continuing RAND basic research in the mathematics of control problems. These problems are a common mathematical formulation of situations that arise in diverse areas. Common examples occur in the control of aircraft and missile regimes, control of chemical reactors, and control of inventories. The present Memorandum treats a class of control problems in which constraints involving the state variable but not explicitly involving the control variable are present.

SUMMARY

This Memorandum studies control problems in which constraints that are independent of the control are imposed on the state variables. Necessary conditions that hold along an optimal trajectory are derived in a relatively simple fashion from known results in the calculus of variations. These results had been obtained by Gambrelidze in a different fashion.

CONTENTS

PREFACE.....	iii
SUMMARY.....	v
Section	
1. INTRODUCTION.....	1
2. FORMULATION OF PROBLEM.....	1
3. EQUIVALENT LAGRANGE PROBLEM.....	4
4. AN INTERIOR SEGMENT.....	10
5. A BOUNDARY SEGMENT.....	11
6. CONCLUSION.....	17
REFERENCES.....	20

ON CONTROL PROBLEMS WITH BOUNDED STATE VARIABLES

1. INTRODUCTION

In a recent paper [1] we showed, among other things, how a fairly general control problem, or programming problem, with constraints can be reduced to a special type of Bolza problem in the calculus of variations. Necessary conditions for the Bolza problem were then translated into necessary conditions for optimal control. These conditions include the maximum principle of Pontryagin [3], [6] for this class of problems and some of the later results of Gamkrelidze [4]. Our results in [1] do not, however, apply to control problems with constraints on the state variables that do not explicitly involve the control variable. Such problems were treated by Gamkrelidze in [4], who modified the arguments in [3] to account for the additional constraints. In this memorandum we shall use the methods of [1] to study such problems, and we shall obtain the results of Gamkrelidze in a very simple fashion from relevant results in the calculus of variations.

2. FORMULATION OF PROBLEM

We assume that the reader is familiar with [1], and we shall use the notation of [1]. Let θ be a function of class C'' on the region D of (t,x) -space such that

the relation $\theta(t,x) = 0$ defines a manifold \mathcal{B}^* which divides \mathcal{D} into two regions. Let \mathcal{B} be that subset of \mathcal{D} defined by the relation

$$(2.1) \quad \theta(t,x) \geq 0 .$$

We shall consider the control problem as formulated in [1] with $g \equiv 0$, and with the added restriction that the curves K resulting from controls u in \mathcal{A} must lie in \mathcal{B} . That is, we consider the following problem.

Problem I. Find an element u^* in the class of admissible controls \mathcal{A} that minimizes the functional

$$J(u) = \int_{t_0}^{t_1} f(t,x,u)dt .$$

Here, the state of the system is determined by the system of differential equations

$$x' = G(t,x,u), \quad x(t_0) = x_0 ;$$

the controls and the state of the system satisfy the constraints

$$R(t,x,u) \geq 0, \quad \theta(t,x) \geq 0 ;$$

and the right-hand end point (t_1, x_1) of the trajectory is a point of a p -dimensional manifold, $0 \leq p \leq n$.

It will be clear from what follows and from [1] how one handles the case in which \mathcal{B} is a closed region in

\mathcal{D} with piecewise smooth boundary, each piece of which is defined by a relation $\theta_i(t,x) = 0$.

The assumption that $g \equiv 0$ is made in order to simplify a certain portion of the argument below. No loss of generality will result, for the control problem of [1] is equivalent to a control problem in which $g \equiv 0$ and the initial point lies on a line, as the following transformation shows. Let a new coordinate x^{n+1} be introduced by means of the following differential equation and end conditions:

$$\frac{dx^{n+1}}{dt} = 0, \quad x_1^{n+1} = \frac{g(\sigma)}{t_1(\sigma) - t_0}, \quad x_0^{n+1} \text{ free.}$$

Let the functional to be minimized be

$$J(u) = \int_{t_0}^{t_1} (f + x^{n+1}) dt .$$

In Problem I we assumed, as we did in [1], that the left-hand end point (t_0, x_0) is fixed. If (t_0, x_0) is constrained to lie on a p -dimensional manifold ($1 \leq p \leq n$) in (t,x) -space, the analysis that follows requires the introduction of a transversality condition for the left-hand end point. We leave this to the reader.

We cannot treat Problem I by simply adjoining the constraint (2.1) as an $(r+1)$ -st component to the constraint vector $R(t,x,u)$ and then proceeding to use

the analysis of [1]. The reason is that since θ is independent of u , the constraint vector (R, θ) will not satisfy the constraint condition (2.2)-(ii) of [1] at any point of \mathcal{B}^* , the manifold defined by $\theta(t, x) = 0$. The constraint conditions for Problem I are the following, which are modifications of those in [1]:

- (2.2) (i) If $r > m$, then at each point of $\mathcal{S} = \mathcal{B} \times \mathcal{U}$, at most m components of R can vanish.
- (ii) If $r \geq m$, then at each point of $\mathcal{S}^* = \mathcal{B}^* \times \mathcal{U}$, at most $(m-1)$ components of R can vanish.
- (ii) At each point of \mathcal{S} the matrix $(\partial R^i / \partial u^j)$, where i ranges over those indices such that $R^i(t, x, u) = 0$, and $j = 1, \dots, m$, has maximum rank. At each point of \mathcal{S}^* , if the m -dimensional row vector $\theta_x G_u$ is adjoined to this matrix, the resulting matrix has maximum rank.

3. EQUIVALENT LAGRANGE PROBLEM

Let η be a scalar, and let

$$(3.1) \quad \gamma(t, x, \eta) = \begin{cases} \eta^4 - \theta(t, x) & \text{if } \eta \geq 0, \\ \theta(t, x) & \text{if } \eta \leq 0. \end{cases}$$

The function $\gamma(t, x, \eta)$ is clearly C'' on the region of (t, x, η) -space which is the Cartesian product of the η -axis and \mathcal{D} . If we let

$$y' = u, \quad y(t_0) = 0,$$

then Problem I is readily seen to be equivalent to the following problem of Lagrange in $(n + m + r + 2)$ -dimensional (t, x, y, ξ, η) -space.

Problem II. Find an arc $(x(t), y(t), \xi(t), \eta(t))$ that minimizes

$$(3.2) \quad \int_{t_0}^{t_1} f(t, x, y') dt$$

in the class of arcs that are piecewise C'' and that satisfy the differential equations

$$(3.3) \quad \begin{aligned} G(t, x, y') - x' &= 0, \\ R(t, x, y') - (\xi')^2 &= 0, \\ \theta_t + \theta_x x' - \gamma_\eta \eta' &= 0, \end{aligned}$$

and also the end conditions

$$(3.4) \quad x(t_0) = x_0, \quad y(t_0) = 0, \quad \xi(t_0) = 0, \quad \gamma(t_0, x_0, \eta_0) = 0,$$

$$(3.5) \quad \begin{aligned} t_1 &= t_1(\sigma), \quad x_1 = x_1(\sigma), \quad \gamma(t_1, x_1, \eta_1) = 0, \\ \xi_1 &= \xi(t_1), \text{ free}, \quad y_1 = y(t_1), \text{ free}. \end{aligned}$$

Note that the last equation in (3.3) and the end conditions imply that $\gamma(t, x, \eta) = 0$ along each arc. Hence, by (3.1), $\theta \geq 0$ along each arc.

Let us suppose that u^* is an optimal control in \mathcal{A} , and let K^* be the corresponding curve in (t, x) -space. Let K_1^* be the corresponding arc in (t, x, y, ξ, η) -space.

Consider the following $(n + r + 1)$ by $(m + n + r + 1)$ matrix along K_1^* :

$$(3.6) \quad \begin{pmatrix} G_{y'} - I & 0 & 0 \\ R_{y'} & 0 - 2\xi' & 0 \\ 0 & \theta_x & 0 & -\gamma_\eta \end{pmatrix},$$

where $2\xi'$ is an $r+r$ diagonal matrix with entries $2(\xi^i)'$ on the diagonal. The rank of (3.6) is clearly the same as the rank of the matrix

$$(3.7) \quad \begin{pmatrix} G_{y'} - I & 0 & 0 \\ R_{y'} & 0 - 2\xi' & 0 \\ \theta_x G_{y'} & 0 & 0 & -\gamma_\eta \end{pmatrix}.$$

Since $\gamma = 0$ along K_1^* , it follows from (3.1) that $\gamma_\eta > 0$ if $\theta > 0$, and that $\gamma_\eta = 0$ if $\eta \leq 0$. Hence, using the constraint conditions (2.2) and arguments similar to those used to determine the rank of (3.8) in [1], we see that the matrix (3.7) has rank $(n + r + 1)$ at all points of K_1^* . Hence (3.6) has rank $(n + r + 1)$.

The above argument is not restricted to K_1^* ; it shows that (3.6) has rank $(n + r + 1)$ at all elements $(t, x, y, \xi, \eta, x', y', \xi', \eta')$ of a curve for which (3.3) and the end conditions (3.4) and (3.5) hold.

If $t_1(\sigma)$ and $x_1(\sigma)$ define a p -dimensional terminal manifold for Problem I, then the right-hand end conditions for Problem II and the restriction that

(t_1, x_1) is in \mathcal{B} determine a p -dimensional terminal manifold in (t, x, η) -space for Problem II. We suppose that in a neighborhood of the right-hand end points of K_1^* , this manifold is given parametrically as follows:

$$t_1 = t_1(s), \quad x_1 = x_1(s), \quad \eta_1 = \eta_1(s).$$

We note that

$$(3.8) \quad \gamma(t_1(s), x_1(s), \eta_1(s)) \equiv 0.$$

Since u^* is an optimal control, it is clear that K_1^* furnishes a minimum for Problem II. From this and from the preceding discussion it follows that the multiplier rule, the Weierstrass condition, and the Clebsch condition as given in Bliss [2] and extended by McShane [5] hold along K_1^* . The function F in this instance is defined as follows:

$$(3.9) \quad F = \psi_0 f + \psi(G - x') + \mu(R - (\xi')^2) + \nu(\theta_t + \theta_x x' - \gamma_\eta \eta').$$

From the Euler equations

$$\frac{dF_{y'}}{dt} = F_y, \quad \frac{dF_{\xi'}}{dt} = F_\xi,$$

the continuity of $F_{y'}$ and $F_{\xi'}$, and the relations

$$(3.10) \quad F_{y'} = 0, \quad F_{\xi'} = 0 \quad \text{at} \quad (t_1, x_1, \eta_1),$$

which we obtain from the transversality condition, we deduce as we did in [1] that along K_1^* ,

$$(3.11) \quad F_{\xi_i} = \mu^i R^i = 0, \quad i = 1, \dots, r,$$

$$F_{y_i} = \psi_0 f_{y_i} + \psi G_{y_i} + \mu R_{y_i} = 0.$$

From the Euler equation $dF_{\eta_i}/dt = F_{\eta_i}$ we find that between corners of K_1^* ,

$$(3.12) \quad v' \gamma_{\eta_i} = 0.$$

The Euler equation $dF_{x_i}/dt = F_{x_i}$ takes the form

$$(3.13) \quad \frac{d}{dt} (-\psi + v \theta_x) = \psi_0 f_x + \psi G_x + \mu R_x + v(\theta_{tx} + \theta_{xx} x').$$

If we make use of (3.10) in the remaining equations of the transversality condition, we get

$$(F - x' F_{x'} - \eta' F_{\eta'}) t_{1s} + F_{x'} x_{1s} + F_{\eta'} \eta_{1s} = 0.$$

From (3.3) we obtain that $x' = G$ and that $F = \psi_0 f$ at (t_1, x_1, η_1) . Using this and the last equation in (3.3), we can rewrite the preceding equation as follows:

$$(\psi_0 f + \psi G) t_{1s} - \psi x_{1s} + v(\theta_t t_{1s} + \theta_x x_{1s} - \gamma_{\eta} \eta_{1s}) = 0.$$

Hence, using (3.8) we find that the transversality condition, in addition to yielding (3.10), gives

$$(3.14) \quad (\psi_0 f + \psi G) t_{1s} - \psi x_{1s} = 0.$$

Another necessary condition is the continuity along K_1^* of the expression

$$F - x' F_{x'} - y' F_{y'} - \xi' F_{\xi'} - \eta' F_{\eta'} .$$

If we take (3.3) and (3.10) into account, this expression may be rewritten as follows along K_1^* :

$$(3.15) \quad \psi_0 f + \psi G + \nu \theta_t .$$

Using arguments similar to those used above and in [1], we may rewrite the Weierstrass condition in the following form:

$$(3.16) \quad \psi_0 (f(t, x, Y') - f(t, x, y')) + \psi (X' - x') \geq 0 .$$

From the Clebsch condition we deduce, as we did in [1], that along K_1^* ,

$$(3.17) \quad \mu \leq 0 ,$$

and that

$$(3.18) \quad e((\psi_0 f + \psi G + \mu R)_{y', y'}) e \geq 0$$

for all m -dimensional solution vectors e of the following linear systems: $\hat{R}_{y'} e = 0$ at points that are interior to \mathcal{B} ; $\hat{R}_{y'} e = 0$ and $\theta_x G_{y'} e = 0$ at points of K_1^* that correspond to points of \mathcal{B}^* . The vector \hat{R} is obtained from R by taking those components of R that vanish at the point.

4. AN INTERIOR SEGMENT

We now consider the curve K^* corresponding to the optimal control u^* . We adopt Gamkrelidze's definition [4] and say that the point $(\tau, x(\tau))$ of K^* is a junction point if $t_0 < \tau < t_1$ and if there exists a $\delta > 0$ such that either the segment of K^* for which $\tau - \delta < t < \tau$, or the segment for which $\tau < t < \tau + \delta$ (or both), lies in the interior of \mathcal{B} . We call τ a junction time. We suppose that K^* has a finite number of junction points. Explicitly, we suppose that if τ is the largest junction time, then the portion of K^* defined for $\tau < t < t_1$ is interior to \mathcal{B} . We denote this segment by K_A^* and also use this notation for the corresponding segment of K_1^* .

Since K_A^* is interior to \mathcal{B} , it follows that $\eta > 0$. Hence from (3.1) we have $\gamma_\eta > 0$, and so from (3.12) we get that between corners of K_A^* , v is constant. Moreover, the end condition (3.14) places no restriction on $v(t_1)$. Since v is constant between corners of K_1^* , equation (3.13) can be written as

$$(4.1) \quad \psi' = - (\psi_0 f_x + \psi G_x + \mu R_x) .$$

Note that the differential equation (4.1) and the end conditions (3.14) are independent of the values assigned to v . Using this observation and the fact that that the left-hand end point of K_1^* is fixed, we can see

by examining the proof in [5] that we can always choose $(\psi_0, \psi, \mu) \neq 0$ at the right-hand end point (t_1, x_1) of K_1^* . From the constraint condition (2.2)-(ii) and from (3.11) it follows that μ is determined uniquely as a linear function of (ψ_0, ψ) on the interval $\tau \leq t \leq t_1$. Hence, on this interval, (4.1) can be written as a linear differential equation in ψ , and so if $(\psi_0, \psi) = 0$ at any point of K_A^* , then $(\psi_0, \psi) \equiv 0$. Moreover, in this event $\mu \equiv 0$. Since $(\psi_0, \psi, \mu) \neq 0$ at (t_1, x_1) , we can therefore conclude that $(\psi_0, \psi) \neq 0$ at every point of K_A^* .

Define

$$(4.2) \quad H(t, x, u, \lambda_0, \lambda) = \lambda_0 f + \lambda G .$$

For $\tau < t < t_1$, let

$$(4.3) \quad \lambda_0 = \psi_0, \quad \lambda = \psi ,$$

and take v to be a constant on the entire interval $\tau < t < t_1$. (K_1^* may have corners in this interval.) It follows from (4.1)-(4.3), (3.11), (3.14)-(3.18), and from the relation $y' = u$, that Theorem 2 of [1] holds along K_A^* .

5. A BOUNDARY SEGMENT

Let τ' be the largest of the junction times that are less than τ . If there are none, take $\tau' = t_0$. We next suppose that the segment of K^* defined for $\tau' \leq t \leq \tau$ lies entirely in \mathcal{B}^* . We denote this

segment (and the corresponding segment of K_1^*) by K_B^* . To simplify the exposition we shall suppose that K_B^* has no corners and the same components of R vanish all along K_B^* . If the contrary holds, the argument requires trivial modifications, which we leave to the reader.

Let

$$(5.1) \quad \phi(t, x, u) = \theta_t + \theta_x G .$$

Then along K_B^* , we clearly have

$$(5.2) \quad \phi = 0 .$$

On the interval $\tau' \leq t \leq \tau$, let

$$(5.3) \quad \lambda_0 = \psi_0, \quad \lambda = \psi - v \theta_x .$$

If we substitute (5.3) into (3.13) and use the definition of ϕ given in (5.1) and the definition of H given in (4.2), we can rewrite (3.13) as

$$(5.4) \quad \frac{d\lambda}{dt} = - (H_x + \mu R_x + v \phi_x) .$$

If we substitute (5.3) into the second equation of (3.11) and replace y' by u , we can rewrite this equation as follows:

$$(5.5) \quad H_u + \mu R_u + v \theta_x G_u = 0 .$$

Similarly, the substitution of (5.3) into the Weierstrass condition (3.16) leads to the relation

$$H(t, x, Y') - H(t, x, y') + v \theta_x(X' - x') \geq 0$$

for all admissible (t, x, X', Y') . Since the element (t, x, X', Y') is admissible, it satisfies the last equation of (3.3), and so $\theta_x(X' - x') = \theta_t + \theta_t = 0$. Hence, setting $u = y'$, we can rewrite (3.16) as

$$(5.6) \quad H(t, x, u) \geq H(t, x, u^*)$$

along K_B^* for all admissible u such that $\phi(t, x, u) = 0$.

Finally, equation (3.18) of the Clebsch condition becomes

$$(5.7) \quad e((H + \mu R + v\theta_x G)_{uu})e \geq 0 .$$

From the necessary conditions for Problem II, it follows that there exists a constant $\lambda_0 \geq 0$ and functions (λ, μ, v) such that (5.4) - (5.7) hold along K_B^* . From the constraint condition (2.2)-(ii), it follows that we may solve (5.5) uniquely for (μ, v) as linear functions of (λ_0, λ) . Substitution of this solution into (5.4) yields a system of linear differential equations for λ . Hence if (λ_0, λ) is determined at a point of K_B^* , then the solution λ of (5.4) and the functions (μ, v) are uniquely determined along K_B^* .

From the Weierstrass-Erdmann corner condition for Problem II, we see that

$$(5.8) \quad F_x' = -\psi + v\theta_x$$

is continuous at the junction point $(\tau, x(\tau))$. Thus, if we denote functions along K_A^* by a subscript A and functions along K_B^* by a subscript B, then at $(\tau, x(\tau))$ we have

$$(5.9) \quad -\psi_A^+ + v_A^+ \theta_x = -\psi_B^- + v_B^- \theta_x .$$

Using (4.3) and (5.3), this can be rewritten as

$$(5.10) \quad \lambda_B^- = \lambda_A^+ - v_A^+ \theta_x , \quad v_A^+ \text{ arbitrary.}$$

This relation and the relation

$$(5.11) \quad \lambda_{0B} = \lambda_{0A} = \psi_0 ,$$

which follows from (4.3), (5.3), and the constancy of ψ_0 , therefore serve to determine $(\lambda_0, \lambda, \mu, \nu)$ uniquely along K_B^* .

From the continuity of (3.15), and from (4.3), (5.3), and (5.2), we readily find that at the junction point $(\tau, x(\tau))$,

$$(5.12) \quad H^- = H^+ + v_A \theta_t .$$

With the help of (5.10) and (5.2), this can be rewritten as follows:

$$(5.13) \quad \begin{aligned} \lambda_0(f^- - f^+) + \lambda^+(G^- - G^+) &= 0 , \\ \lambda_0(f^- - f^+) + \lambda^-(G^- - G^+) &= v_A^+ (\theta_x G^+ + \theta_t) . \end{aligned}$$

It is readily verified that the vector

$$(5.14) \quad (\lambda_0, \lambda_B, \mu_B, \nu_B) = (0, \rho \theta_x, 0, -\rho),$$

where ρ is any real constant, satisfies (5.4) and (5.5) along any curve K obtained from an admissible control and lying in \mathcal{B}^* . Substitution of (5.14) into the relation (5.6) reduces (5.6) to the identity $\rho \theta_t = \rho \theta_t$ along any such curve. From (5.5) and the constraint condition (2.2)-(ii) it follows that (5.14) is the unique solution of (5.4)-(5.6) with $\lambda_0 = 0$, $\lambda = \rho \theta_x$, ρ arbitrary. It is immediate from (5.3) that for Problem II,

$$(5.15) \quad (\psi_0, \psi_B, \mu_B, \nu_B) = (0, 0, 0, -\rho), \rho \text{ arbitrary,}$$

is the unique vector corresponding to (5.14). The vector (5.15) reduced the Euler equations (3.13) and (3.11), and the Weierstrass condition (3.16) to identities for all admissible curves lying in \mathcal{B}^* . We shall refer to (5.14) or (5.15) as a trivial multiplier vector. Note that since ρ is arbitrary, the zero vector is included.

If we have

$$(5.16) \quad \lambda_0^+ = 0, \quad \lambda_A^+ = k \theta_x, \quad k \neq 0,$$

at $(\tau, x(\tau))$, for every set of multipliers $(\lambda_0, \lambda_A, \mu_A, \nu_A)$ such that equations (5.4)-(5.7) hold along K_A^* , then it follows from (5.10) and the discussion of the preceding paragraph that along the segment K_B^* we obtain the trivial multipliers (5.14). To avoid this, we proceed

as follows. We consider a Problem I', which we define as Problem I with fixed initial point $(\tau', x(\tau'))$ and fixed terminal point $(\tau, x(\tau))$. It is clear that the segment K_B^* must furnish a relative minimum for Problem I'. For, if some other curve K' furnished a minimum, then we could replace the segment K_B^* of K^* by K' and thereby contradict the minimality of K^* . Since the Lagrange problem corresponding to Problem I' has fixed end points, it can be seen from the proof in [5] of the necessary conditions that we may take $(\psi_0, \psi(\tau_2)) \neq 0$. Hence there exist nontrivial multipliers (ψ_0, ψ, μ, ν) such that (5.4)–(5.7) hold along K_B^* , even if (5.16) holds. In this event, however, (5.10)–(5.13) are no longer valid.

The following theorem is a consequence of the preceding discussion.

Theorem 1. On the interval $[\tau', \tau]$ there exists a constant $\lambda_0 \geq 0$ and a continuous n -dimensional vector $\lambda(t)$ such that $(\lambda_0, \lambda) \neq (0, \rho \theta_x)$, ρ arbitrary; an n -dimensional vector $\mu(t) \leq 0$, continuous except perhaps at values of t corresponding to corners of K_B^* ; and a function $\nu(t)$ with the same continuity properties as μ , such that along K_B^* , (5.4)–(5.7) hold.

At the junction point $(\tau, x(\tau))$, either (5.6) holds for every $(\lambda_{0A}, \lambda_A^+)$, or the jump conditions (5.10) and (5.12) (and hence (5.13)) hold.

Remark 1. This result was obtained by Gamkrelidze [4], who used different arguments. He also presents a result that in our notation reads $dv/dt \geq 0$ along K_B^* .

Remark 2. In Sec. 4 we assumed that the segment K_A^* was interior to \mathcal{S} . If we had assumed that the segment K_A^* was in \mathcal{S}^* , then we would still conclude that, except for the jump conditions, Theorem 1 holds along K_A^* . This follows from the arguments used to establish the theorem and the observation that the transversality condition (3.14) places no restriction on $v(t_1)$.

6. CONCLUSION

If $\tau' > t_0$, let us suppose that τ'' is the largest junction time that is less than τ' ; if there is no such junction time, take $\tau'' = t_0$. The segment of K^* defined for $\tau'' < t < \tau'$ then lies entirely within \mathcal{S} . We denote this segment by K_C^* . On this segment we define (λ_0, λ) by means of (4.3), and apply the analysis of Sec. 4, except for the determination of initial data for (4.1). We now use the continuity of (5.8) at the junction point to determine λ_{0C} and $\lambda_C(\tau'')$, where the subscript C refers to functions along K_C^* . Since we have $(\lambda_0, \lambda_B^-) \neq (0, \rho\theta_x)$, it follows that at $(\tau'', x(\tau''))$, the following jump condition holds:

$$\lambda_C^- = \lambda_B^+ + v_C^- \theta_x \neq 0, \quad v_C^- \text{ arbitrary.}$$

Hence the conclusions of Theorem 2 of [1] hold along K_C^* .

Let us now suppose that K_B^* , instead of lying on the boundary as assumed in Sec. 5, is an interior segment.

The point $(\tau, x(\tau))$, however, is still assumed to be a junction point. Along K_B^* we now define $(\lambda_{0B}, \lambda_B)$ by (4.3), and we apply the analysis of Sec. 4, except for the determination of the initial data for $(\lambda_{0B}, \lambda_B)$.

To determine λ_{0B} and $\lambda_B(\tau)$ we use the continuity of (5.8) and get

$$\lambda_B^- = \lambda_A^+ + (v_B^- - v_A^+) \theta_x.$$

Since we are free in our choice of v_B^- , we get

$$(6.1) \quad \lambda_B^- = \lambda_A^+ + k \theta_x \neq 0.$$

Hence Theorem 2 of [1] holds along K_B^* .

Note that in obtaining (6.1), we did not make use of the special fact that v_A^+ is arbitrary because the segment K_A^* terminates at (t_1, x_1) . Moreover, we can choose v_B^- so that $k \geq 0$.

We summarize the principal results of this paper in the following theorem.

Theorem 2. Let $u^* \in \mathcal{A}$ be an optimal control, and let K^* be the corresponding curve. Then there exists a constant $\lambda \geq 0$, an n -dimensional vector $\lambda(t)$, an r -dimensional vector $\mu(t) \leq 0$, and a function $v(t)$ such that the following hold: Along a segment of K^* whose end points are junction points and that is in the interior of \mathcal{B} , except for the end-points, Theorem 2 of [1] holds. Along a segment whose end-points are junction points and that lies in \mathcal{B}^* , Theorem 1 of this paper holds. At a junction point either

$$(6.2) \quad \lambda_0 = 0, \quad \lambda^- + k \theta_x = 0, \quad k \neq 0,$$

or

$$(6.3) \quad \lambda^+ = \lambda^- + k \theta_x \neq 0.$$

At a junction point between two interior segments, (6.2) does not occur, and we may take $k \geq 0$ in (6.3). If (6.3) holds, then the following also holds:

$$(6.4) \quad H^+ = H^- - k \theta_t.$$

From this theorem, several observations can be made. Since these are given by Gamkrelidze [4], there is no need to repeat them here.

REFERENCES

1. Berkovitz, L. D., "Variational Methods in Problems of Control and Programming," J. Math. Anal. Appl. Vol. 3, 1961, pp. 145-169.
2. Bliss, G. A., Lectures in the Calculus of Variations, University of Chicago Press, Chicago, Illinois, 1946.
3. Boltyanskii, V. G., R. V. Gamkrelidze, and L. S. Pontryagin, "The Theory of Optimal Processes I: The Maximum Principle," Izv. Akad. Nauk. SSSR, Ser. Mat., Vol. 24, 1960, pp. 3-42.
4. Gamkrelidze, R. V., "Optimal Processes with Bounded Phase Coordinates," Izv. Akad. Nauk. SSSR, Ser. Mat., Vol. 24, 1960, pp. 315-356.
5. McShane, E. J., "On Multipliers for Lagrange Problems," Am. J. Math., Vol. 61, 1939, pp. 809-819.
6. Pontryagin, L. S., "Optimal Control Processes," Uspekhi Mat. Nauk., Vol. 14, 1959, pp. 3-20.