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Characterisation of the value function of final state constrained control problems with BV trajectories*

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Abstract

This paper aims to investigate a control problem governed by differential equations with Random measure as data and with final state constraints. By using a known reparametrization method (by Dal Maso and Rampazzo [16]), we obtain that the value function can be characterized by means of an auxiliary control problem involving absolutely continuous trajectories. We study the characterization of the value function of this auxiliary problem and discuss its discrete approximations.

Keywords: Optimal control problem, differential systems with measures as data, measurable functions, Hamilton-Jacobi equations

AMS Classification: 49J15, 35F21, 34A37

1 Introduction

In this paper we investigate, via a Hamilton-Jacobi-Bellmann approach, a final state constrained optimal control problem with a Radon measure term in the dynamics.

Several real applications can be described by optimal control problems involving discontinuous trajectories. For instance, in space navigation area, when steering a multi-stage launcher, the separation of the boosters (once they are empty) lead to discontinuities in the mass variable [9]. In resource management, discontinuous trajectories are also used to modelize the problem of sequential batch reactors (see [19]). Many other applications can be found in the Refs. [8, 14, 15, 17].

Consider the controlled system:

$$dY(t) = \sum_{i=1}^M g_i(t, Y(t), \alpha(t)) d\mu_i + g_0(t, Y(t), \alpha(t)) dt \quad \text{for } t \in (\tau, T] \quad (1.1a)$$

$$Y(\tau^-) = X. \quad (1.1b)$$

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where $x \in \mathbb{R}^N$, the measurable control $\alpha : (0, +\infty) \rightarrow \mathbb{R}^m$ takes values in a compact set $\mathcal{A} \subset \mathbb{R}^m$, and $\mu = (\mu_1, \dots, \mu_M)$ is a given Radon measure. Let $\varphi : \mathbb{R}^N \rightarrow \mathbb{R}$ be a given lower semicontinuous (lsc) function, and consider the control problem:

$$v(X, \tau) := \inf\{\varphi(Y_{X,\tau}^\alpha(T)) : \alpha(\cdot) \in L^\infty(0, T; \mathcal{A}), \text{ and } Y_{X,\tau}^\alpha \text{ satisfies (1.1)}\}. \quad (1.2)$$

Due to the presence of the measure μ , the definition of solution for the state equation (1.1) is not classical. We will refer to the definition introduced by Dal Maso and Rampazzo in [16] using the technique of graph completion (Definition 2.1 in Section 2 below). Roughly speaking, by a suitable change of variable in both time and the primitive of μ , we can reduce (1.1) to usual controlled ordinary differential equation (ode) with a measurable time-dependent dynamics (see Theorem 2.2 below). Note that several works have been done to study the impulsive control problems, i.e. when the measures appear as controls. We refer to [26] for existence of optimal trajectories, and to [1] for first and second necessary optimality conditions.

Here, in problem (1.2), the measure is given by the model and the state equation is controlled by means of a measurable function α . Our main goal is to use the HJB approach in order to characterize the value function v and then to study a numerical method to compute this function.

Since the value function v fulfils a Dynamic Programming Principle (DPP), we can derive, at least formally, the following HJB equation

$$\begin{cases} -v_t(X, t) + \sup_{a \in \mathcal{A}} \left\{ -Dv(t, X) \cdot \left(g_0(t, X, a) + \sum_{i=1}^M g_i(t, X, a) \mu_i \right) \right\} = 0; \\ v(X, T) = \varphi(X). \end{cases} \quad (1.3)$$

Clearly, the main difficulty is to give a meaning to the term “ $Dv \cdot \mu$ ” knowing that one can not expect to have a differentiable value function. In order to overcome this problem, following the ideas in [12], we define a new value function \bar{v} such that:

$$v(X, \tau) = \bar{v}(X, \mathcal{W}(\tau)),$$

where \mathcal{W} is the known change of variable coming from the graph completion technique (See Theorem 2.4). The advantage is that now the HJB equation for \bar{v} has a t -measurable Hamiltonian and not a measure term. More precisely, we can prove that \bar{v} is a solution of the following equation:

$$\begin{cases} -v_s(X, s) + H(s, X, D\bar{v}(X, s)) = 0; \\ \bar{v}(X, 1) = \varphi(X); \end{cases} \quad (1.4)$$

where $H(t, x, p) = \sup_{a \in \mathcal{A}} \{-p \cdot \mathcal{F}(t, x, a)\}$ and $\mathcal{F}(t, x, a)$ is a t -measurable dynamics (see Section 2.2 for the definition of \mathcal{F}). Due to the double presence of an only t -measurable Hamiltonian and a lsc final data, the definition of viscosity solution is still not classical.

We recall that, in the case when φ is continuous, the definition of viscosity solution for t -measurable Hamiltonians has been introduced by Ishii in 1985 (see [20]) and then studied for the second order case by Nunziante in [24]-[25](see also the work of Lions-Perthame [21] and Briani-Rampazzo [13]). Moreover, a very general stability result has been proved more recently by Barles in [3]. On the other side, to deal with the case when the Hamiltonian H is continuous with respect

to the time variable and the final data φ is lsc, the definition of bilateral viscosity solution has been introduced by Barron and Jensen in 1990 ([6]) and by Frankowska [18].

In this paper, since we deal with target problem, the function φ is lsc and the Hamiltonian in (1.4) is only t -measurable. We introduce a new definition of viscosity solution of (1.4), namely the definition of L^1 -bilateral viscosity solution (Definition 3.2 below). This definition allows to characterize \bar{v} as the unique L^1 -bilateral viscosity solution of equation (1.4) (Theorem 3.4). It gives also a suitable framework to deal with the numerical approximation of \bar{v} (and then of v by the change of variable \mathcal{W}). More precisely, we prove in Theorem 3.6 a convergence result for monotone, stable and consistent numerical schemes, and give an example of a scheme satisfying these properties. Some numerical tests are presented in Subsection 3.2.

On the other hand, we study the properties of L^1 -bilateral viscosity solution for a general HJB equation. In particular, we derive under classical assumptions on the Hamiltonian (see in Section 4), the consistency of the definition (Theorem 4.7), a general stability result w.r. to the Hamiltonian (Theorem 4.9), a stability result w.r. to the final data (Theorem 4.10), and uniqueness result (Theorem 4.11).

This paper is organised as follows. In Section 2 we set the optimal control problem we are considering. Subsection 2.1 is devoted to the definition of solution for the state equation while Subsection 2.2 to the construction of the reparametrised optimal control problem and the definition of \bar{v} . In Section 3 we consider the optimal control problem for the t -measurable HJB equation, we state the definition of L^1 -bilateral viscosity solution, and we prove that the value function \bar{v} is the L^1 -bilateral viscosity solution of equation (1.4) in Theorem 3.4. Subsection 3.1 is devoted to the convergence result and to the construction of a good approximating scheme while in Subsection 3.2 we give some numerical test.

Finally in Section 4 we will prove the consistency (Theorem 4.7), stability (Theorem 4.9 and 4.10) and uniqueness (Theorem 4.11) result for L^1 -bilateral viscosity solution.

Notations. For each $r > 0$, $x \in \mathbb{R}^N$ we will denote by $B_r(x)$ the closed ball of radius r centred in x . Given a Radon measure μ we will denote by $L^1_\mu(\mathbb{R})$ the space of L^1 -functions with respect to the measure μ .

For a function $f : [a, b] \rightarrow \mathbb{R}^N$ we will denote by $V_a^b(f)$ the classical variation on $[a, b]$ and by $BV([0, T]; \mathbb{R}^N)$ the set of functions $f : [0, T] \rightarrow \mathbb{R}^N$ with bounded variation on $[0, T]$. Moreover, we will denote by $BV^-([0, T]; \mathbb{R}^N)$ the set of left continuous functions of $BV([0, T]; \mathbb{R}^N)$ which are continuous at 0.

In all the sequel, we will use the classical notations: $f(t^+) := \lim_{s \rightarrow t^+} f(s)$ and $f(t^-) := \lim_{s \rightarrow t^-} f(s)$. And finally, we will denote by $AC([0, 1]; \mathbb{R}^N)$ the set of absolutely continuous functions from $[0, 1]$ to \mathbb{R}^N .

2 The optimal control problem with BV trajectories

In this section we state the final state constrained optimal control problem we consider. First, we recall the definition of solution for the state equation introduced by Dal Maso and Rampazzo in [16] and we recall the graph completion construction. Then, we define the value function, we construct the reparametrised optimal control problem and we prove that the two value functions are linked by a change of variable.

2.1 The state equation

Let us fix $0 \leq \tau < T$, an initial data $X \in \mathbb{R}^N$, a given Radon measure $\mu = (\mu_1, \dots, \mu_M)$, a control variable $\alpha \in \mathcal{A}$, and consider the controlled trajectory $Y_{X,\tau}^\alpha : \mathbb{R}^+ \rightarrow \mathbb{R}^N$ solution of:

$$\begin{cases} dY(t) = \sum_{i=1}^M g_i(t, Y(t), \alpha(t)) d\mu_i + g_0(t, Y(t), \alpha(t)) dt & \text{for } t \in (\tau, T] \\ Y(\tau^-) = X. \end{cases} \quad (2.5)$$

We assume the following:

(Hco) The set of controls is $\mathcal{A} := L^\infty((0, T); A) \cap L^\infty_\mu((0, T); A)$ where A is a compact subset of \mathbb{R}^m , $m \geq 1$.

(Hg1) The functions $g_i(t, Y, \alpha) : \mathbb{R}^+ \times \mathbb{R}^N \times A \rightarrow \mathbb{R}^N$, ($i = 0, \dots, M$), are measurable functions in t and continuous in (Y, α) . Moreover, for each $Y \in \mathbb{R}^N, \alpha \in A$ we have $g_0(\cdot, Y, \alpha) \in L^1(\mathbb{R}^+)$ and $g_i(\cdot, y, \alpha) \in L^1_{\mu_i}(\mathbb{R}^+), (i = 1, \dots, M)$.

(Hg2) There exists a function $k_0 \in L^\infty(\mathbb{R}^+; \mathbb{R}^+)$ such that

$$|g_i(t, Y, \alpha) - g_i(t, Z, \alpha)| \leq k_0(t) |Y - Z| \quad \forall Y, Z \in \mathbb{R}^N, \alpha \in A, \text{ and a.e } t \in \mathbb{R}^+, i = 0, \dots, M.$$

(Hg3) There exist $K > 0$ such that

$$|g_i(t, Y, \alpha)| \leq K \quad \forall Y \in \mathbb{R}^N, \alpha \in A, \text{ and a.e } t \in \mathbb{R}^+, i = 0, \dots, M.$$

Following [16], we introduce the left continuous primitive B of the Radon measure μ , i.e. $B \in BV^-([0, T]; \mathbb{R}^M)$ and his distributional derivative \dot{B} coincides with μ on $[0, T]$. In all the sequel, we will denote by $\mathcal{T} := \{t_i, i \in \mathbb{N}\}$ the countable subset of $[0, T)$ which contains 0 and all the discontinuity points of B and by E_c the set of all continuity points of B . Furthermore, let $(\psi_t)_{t \in \mathcal{T}} := (\psi_t^1, \dots, \psi_t^M)$ be a family of Lipschitz continuous maps from $[0, 1]$ into \mathbb{R}^M such that

$$\sum_{t \in \mathcal{T}} V_0^1(\psi_t) < \infty, \quad \psi_t(0) = B(t^-), \text{ and } \psi_t(1) = B(t^+) \quad \forall t \in \mathcal{T}; \quad (2.6)$$

(if $t = 0$ we require only $\psi_t(1) = B(0^+)$). We will denote by ξ the solution of:

$$\frac{d\xi}{d\sigma} = \sum_{i=1}^M g_i(\sigma, \xi(\sigma), \alpha(\sigma)) \frac{d\psi_t^i}{d\sigma} \quad \text{for } \sigma \in (0, 1] \quad \xi(0) = \bar{\xi},$$

and we set $\xi(\bar{\xi}, \psi_t) := \xi(1) - \bar{\xi}$.

We are finally ready to state the definition of solution introduced by Dal Maso and Rampazzo in [16, Definition 5.1].

Definition 2.1. Fix an initial datum and time (X, τ) and control variable $\alpha \in \mathcal{A}$, the function $Y_{X,\tau}^\alpha \in BV([\tau, T]; \mathbb{R}^N)$ is a solution of (2.5) if for each Borel subset \mathcal{B} of $]\tau, T[$ we have

$$\int_{\mathcal{B}} dY(t) = \int_{\mathcal{B}} g(t, Y(t), \alpha(t)) dt + \sum_{i=1}^M \int_{\mathcal{B} \cap E_c} g_i(t, Y(t), \alpha(t)) d\mu_i + \sum_{t \in \mathcal{T} \cap \mathcal{B}} \xi(Y(t^-), \psi_t) \quad (2.7)$$

and $Y(\tau^-) = X$. Moreover, if $\tau \in \mathcal{T}$ we have $Y(\tau^+) = \xi(X, \psi_\tau)$.

In order to prove the uniqueness of this solution we set

$$a_i := V_0^1(\psi_{t_i}), \quad a := \sum_{i=1}^{+\infty} a_i, \quad w(t) := \frac{t + V_0^t(B)}{T + V_0^T(B)}, \quad (2.8)$$

and we define $\mathcal{W} : [0, T] \rightarrow [0, 1]$ as follows:

$$\mathcal{W}(t) := \frac{1}{1+a} \left(w(t) + \sum_{t_i < t} a_i \right). \quad (2.9)$$

The graph completion of B corresponding to the family $(\psi_t)_{t \in \mathcal{T}}$ is then defined by:

$$\Phi(s) = (\phi^0; \phi^1, \dots, \phi^M)(s) = \begin{cases} (t; B(t)) & \text{if } s = \mathcal{W}(t) & t \in [0, T] \setminus \mathcal{T} \\ (t_i; \psi_{t_i} \left(\frac{s - \mathcal{W}(t_i)}{\mathcal{W}(t_i^+) - \mathcal{W}(t_i)} \right)) & \text{if } s \in [\mathcal{W}(t_i), \mathcal{W}(t_i^+)] & t_i \in \mathcal{T}. \end{cases} \quad (2.10)$$

We are ready now to construct the reparametrisation of system (2.5). Let $\sigma := \mathcal{W}(\tau)$, for each control $\alpha \in \mathcal{A}$ and initial datum X we denote by $Z_{X,\sigma}^\alpha : [\sigma, 1] \rightarrow \mathbb{R}^N$ the solution of

$$\begin{cases} \frac{dZ}{ds}(s) = \sum_{i=1}^M g_i(\phi^0(s), Z(s), \alpha(\phi^0(s))) \left(\mu^a(\phi^0(s)) \frac{d\phi^0}{ds}(s) + \frac{d\phi^i}{ds}(s) \right) + \\ \quad g_0(\phi^0(s), Z(s), \alpha(\phi^0(s))) \frac{d\phi^0}{ds}(s) & \text{for } s \in (\sigma, 1] \\ Z(\sigma) = X \end{cases} \quad (2.11)$$

where μ^a is the absolutely continuous part of the measure μ with respect to the Lebesgue measure, i.e. $\mu(t) = \mu^a(t)dt + \mu^s$. Note that the derivatives of ϕ^0, ϕ^i are measurable functions, therefore assumptions **(Hg1)**-**(Hg2)** ensure the applicability of Caratheodory's Theorem to obtain the existence of a unique solution of (2.11) in $AC([\sigma, 1]; \mathbb{R}^N)$.

Theorem 2.2. *Assume **(Hco)** and **(Hg1)**-**(Hg3)**. Let μ be a Radon measure and $(\psi_t)_{t \in \mathcal{T}}$ be a family fulfilling (2.6). Then $Y_{X,\tau}^\alpha \in BV([\tau, T]; \mathbb{R}^N)$ is a solution of (2.5) if and only if there exists a solution $Z_{X,\sigma}^\alpha \in AC([\sigma, 1]; \mathbb{R}^N)$ of (2.11) corresponding to the graph completion Φ defined in (2.10) such that*

$$Z_{X,\sigma}^\alpha(\mathcal{W}(t)) = y(t) \quad \forall t \in [\tau, T] \quad (2.12)$$

where \mathcal{W} is given by (2.9).

Moreover, for each Radon measure μ and each family $(\psi_t)_{t \in \mathcal{T}}$ equation (2.5) has a unique solution (up to a set of zero Lebesgue measure).

Proof. The equivalence (2.12) can be obtained by adapting the proof given for $M = N = 1$ in [12, Theorem 2.8]. On the other hand, the uniqueness of the solution is a consequence of Caratheodory's Theorem applied to equation (2.11). \square

Remark 2.3. *We point out that this definition depends on the family $(\psi_t)_{t \in \mathcal{T}}$ we choose. It is now a classical result that under commutativity conditions on the vector fields g_i ($i = 1, \dots, M$) the*

solution does not depend on this choice. In the pioneering works of Bressan and Rampazzo [10, 11] the case when the g_i do not depend on the control and are continuous in t , have been studied. When the g_i depends on the control α we refer to [23] for a precise discussion.

However, in this paper, the dependency on the choice of ψ_t does not imply any specific difficulty in the sequel.

2.2 The control problem

Given a lower semicontinuous function $\varphi : \mathbb{R}^N \rightarrow \mathbb{R}$ and a final time T , our aim is to calculate the following value function

$$v(X, \tau) := \inf_{\alpha \in \mathcal{A}} \varphi(Y_{X,\tau}^\alpha(T)) \quad (2.13)$$

where $Y_{X,\tau}^\alpha$ is the solution of equation (2.5).

It is easy to prove that the following Dynamic Programming Principle holds: for each $\tau \leq h \leq T$ we have

$$v(X, \tau) = \inf_{\alpha \in \mathcal{A}} v(Y_{X,\tau}^\alpha(h), h). \quad (2.14)$$

Therefore we can formally derive a HJB equation:

$$\begin{cases} -v_t(X, t) + H(t, X, Dv(X, t)) = 0 & \text{for } (X, t) \in \mathbb{R}^N \times (0, T), \\ v(X, T) = \varphi(X) & \text{for } X \in \mathbb{R}^N \end{cases} \quad (2.15)$$

where the Hamiltonian is

$$H(t, X, P) = \sup_{a \in \mathcal{A}} \left\{ -P \cdot \left(g_0(t, X, a) + \sum_{i=1}^M g_i(t, X, a) \mu_i \right) \right\}. \quad (2.16)$$

As we said before, in the introduction of the paper, the problem is to give a meaning to the term $Dv \cdot \mu$ knowing that one can not expect to have a differentiable value function.

In view of Theorem 2.2, it is then natural to consider the trajectories $Z_{X,\sigma}^\alpha$ solution of the the reparametrised system (2.11). We define then the corresponding value function as follows:

$$\bar{v}(X, \sigma) = \inf_{\alpha \in \mathcal{A}} \varphi(Z_{X,\sigma}^\alpha(1)). \quad (2.17)$$

The link between the two problems is given by the following result.

Theorem 2.4. *Let v and \bar{v} be respectively defined in (2.13) and (2.17).*

For each $X \in \mathbb{R}^N$ and $\tau \in [0, T]$ we have

$$v(X, \tau) = \bar{v}(X, \mathcal{W}(\tau)) \quad (2.18)$$

where \mathcal{W} is given by (2.9). Moreover

$$v_{\#}(X, \tau) = \bar{v}_{\#}(X, \mathcal{W}(\tau)) \quad \forall X \in \mathbb{R}^N, \quad \forall \tau \in [0, T] \setminus \mathcal{T} \quad (2.19)$$

and

$$v_{\#}(X, \tau) \geq \bar{v}_{\#}(X, \mathcal{W}(\tau)) \quad \forall X \in \mathbb{R}^N, \quad \forall \tau \in \mathcal{T}, \quad (2.20)$$

where we respectively denote by $v_{\#}$ and $\bar{v}_{\#}$ the lower semicontinuous envelope of v and \bar{v} w.r. to both variable (X, τ) and (X, s) .

Proof. By Theorem 2.2 above we have $Y_{X,\tau}^\alpha(T) = Z_{X,\mathcal{W}(\tau)}^\alpha(\mathcal{W}(T)) = Z_{X,\sigma}^\alpha(1)$ then (2.18) follows by the definitions of v and \bar{v} .

Since, by construction $\mathcal{W}(\tau)$ is monotone increasing in $[0, T]$ and continuous in any $\tau \in \mathcal{T}$, (2.19) and (2.20) easily follow. \square

Remark 2.5. In (2.19), (2.20) we stressed the link between the lsc envelopes of v and \bar{v} because is indeed the function $\bar{v}_\#(X, s)$ that will be characterized as solution of an HJB equation.

Thanks to Theorem 2.4, it is clear that we turn now our attention to the HJB equation for the function \bar{v} . The advantage is that we do not have any more measure in the dynamics.

The new value function \bar{v} satisfies also a DPP:

$$\bar{v}(X, \sigma) = \inf_{\alpha \in \mathcal{A}} \bar{v}(Z_{X,\sigma}^\alpha(h), h) \quad \forall \sigma \leq h \leq 1, \text{ and } \forall X \in \mathbb{R}^N. \quad (2.21)$$

From this DPP, one could expect to characterise \bar{v} through the following HJB equation:

$$\begin{cases} -\bar{v}_s(X, s) + H(s, X, D\bar{v}(X, s)) = 0 & \text{for } (X, s) \in \mathbb{R}^N \times (0, 1), \\ \bar{v}(X, 1) = \varphi(X) & \text{for } X \in \mathbb{R}^N \end{cases} \quad (2.22)$$

where the Hamiltonian is

$$H(s, X, P) = \sup_{a \in \mathcal{A}} \left\{ -P \cdot \left(g_0(\phi^0(s), Z(s), \alpha(\phi^0(s))) \frac{d\phi^0}{ds}(s) + \sum_{i=1}^M g_i(\phi^0(s), Z(s), \alpha(\phi^0(s))) \left(\mu^a(\phi^0(s)) \frac{d\phi^0}{ds}(s) + \frac{d\phi^i}{ds}(s) \right) \right) \right\}. \quad (2.23)$$

Note that, by definition (2.10), the graph completion (ϕ^0, ϕ^i) is a Lipschitz function, therefore we can not expect to have a time continuous Hamiltonian. Moreover, our final condition φ is only lower semicontinuous. Thus, we should first give a precise meaning to the definition of the viscosity solution of the equation (2.22).

3 Optimal control problems with measurable time-dependent dynamics

In this Section we prove that the value function \bar{v} is the unique L^1 -bilateral viscosity solution of (2.22), and that the latter can be solved numerically. For the sake of generality we will prove our results in the following more general framework.

The set of controls is $\mathcal{A} := L^\infty(\mathbb{R}^+; A)$, where A is a compact subset of \mathbb{R}^m ($m \geq 1$).

Fix a final time T , given $x \in \mathbb{R}^N$, $\tau \geq 0$ and a control $a \in \mathcal{A}$, we consider the trajectory $y_{x,\tau}^a$, solution of the following system:

$$\begin{cases} \dot{y}(t) = \mathcal{F}(t, y(t), a(t)), & \text{for } t \in (\tau, T) \\ y(\tau) = x. \end{cases} \quad (3.24)$$

For each initial point and time $(x, \tau) \in \mathbb{R}^N \times \mathbb{R}^+$ we set:

$$\vartheta(x, \tau) := \inf_{a \in \mathcal{A}} \varphi(y_{x,\tau}^a(T)). \quad (3.25)$$

We assume the following :

(HF1) $\mathcal{F}(t, x, a) : \mathbb{R}^+ \times \mathbb{R}^N \times A \rightarrow \mathbb{R}^N$ is measurable in t and continuous in x and a . Moreover, for each $(x, a) \in \mathbb{R}^N \times A$ we have $\mathcal{F}(\cdot, x, a) \in L^1(\mathbb{R}^+)$.

(HF2) There exists $k_0 \in L^\infty(\mathbb{R}^+; \mathbb{R}^+)$ such that

$$|\mathcal{F}(t, x, a) - \mathcal{F}(t, z, a)| \leq k_0(t)|x - z| \quad \forall x, z \in \mathbb{R}^N, a \in A, t \in \mathbb{R}^+.$$

(HF3) There exists a $K > 0$ such that

$$|\mathcal{F}(t, x, a)| \leq K \quad \forall x \in \mathbb{R}^N, a \in A, t \in \mathbb{R}^+.$$

(Hid) The function $\varphi : \mathbb{R}^N \rightarrow \mathbb{R}$ is lower semi continuous and bounded.

Remark 3.1. Let us point out that if we assume **(Hg1)**-**(Hg3)**, then the function

$$\mathcal{F}(s, x, a) := \sum_{i=1}^M g_i(\phi^0(s), x, a) \left(\mu^a(\phi^0(s)) \frac{d\phi^0}{ds}(s) + \frac{d\phi^i}{ds}(s) \right) + g_0(\phi^0(s), x, a) \frac{d\phi^0}{ds}(s)$$

fulfils **(HF1)**-**(HF3)**. Therefore, all the results in this section will apply, in particular, to the value function \bar{v} defined in (2.17). Note that, in particular, assumption (3.31) below is fulfilled, therefore the uniqueness will be also guaranteed.

In all the sequel, we denote \mathcal{V} the lower semicontinuous envelope of ϑ defined by:

$$\mathcal{V}(x, t) := \liminf_{y \rightarrow x, s \rightarrow t} \vartheta(y, s). \quad (3.26)$$

Our first aim is then to prove that we can characterize the function \mathcal{V} in (3.26) as the unique L^1 -bilateral viscosity solution (see the definition below) of the following HJB equation:

$$\begin{cases} -\mathcal{V}_t(x, t) + H(t, x, D\mathcal{V}(x, t)) &= 0 & \text{for } (x, t) \in \mathbb{R}^N \times (0, T), \\ \mathcal{V}(x, T) &= \varphi(x) & x \in \mathbb{R}^N \end{cases} \quad (3.27)$$

where the Hamiltonian is

$$H(t, x, p) = \sup_{a \in A} \{-p \cdot \mathcal{F}(t, x, a)\}. \quad (3.28)$$

Definition 3.2. L^1 -bilateral viscosity solution (L1Bvs)

Let $u : \mathbb{R}^N \times (0, T) \rightarrow \mathbb{R}$ be a bounded lsc function. We say that u is a L^1 -bilateral viscosity solution (L1Bvs) of (3.27) if:

for any $b \in L^1(0, T)$, $\phi \in C^1(\mathbb{R}^N)$ and (x_0, t_0) local minimum point for $u(x, t) - \int_0^t b(s)ds - \phi(x)$ we have

$$\lim_{\delta \rightarrow 0^+} \operatorname{ess\,sup}_{|t-t_0| \leq \delta} \sup_{x \in B_\delta(x_0), p \in B_\delta(D\phi(x_0))} \{H(t, x, p) - b(t)\} \geq 0 \quad (3.29)$$

and

$$\lim_{\delta \rightarrow 0^+} \operatorname{ess\,inf}_{|t-t_0| \leq \delta} \inf_{x \in B_\delta(x_0), p \in B_\delta(D\phi(x_0))} \{H(t, x, p) - b(t)\} \leq 0. \quad (3.30)$$

Moreover, the final condition is satisfied in the following sense:

$$\varphi(x) = \inf \left\{ \liminf_{n \rightarrow \infty} u(x_n, t_n) : x_n \rightarrow x, t_n \uparrow T \right\}.$$

Remark 3.3. *For the sake of clarity, we will state and prove, in Section 4, the consistency, stability and uniqueness result for the viscosity sense (L1Bvs) defined in Definition 3.2.*

Let us now prove the characterisation of the value function.

Theorem 3.4. *Assume (HF1)-(HF3) and (Hid). The function defined in (3.26) is a L^1 -bilateral viscosity solution of (3.27) when the Hamiltonian is given in (3.28).*

If, moreover, there exists a continuous function $\omega : \mathbb{R}^+ \rightarrow \mathbb{R}$ such that $\omega(0) = 0$ and

$$|H(t, x, p) - H(s, x, p)| \leq \omega(|t - s|)|p| \quad \forall p \in \mathbb{R}^N, \forall x \in \mathbb{R}^N, \forall t, s \in \mathbb{R}^+ \quad (3.31)$$

then (3.27) admits a unique L^1 -bilateral viscosity solution.

Proof. This proof follows the ideas of Barron and Jensen in [7]. First, it is easy to verify that \mathcal{V} fulfils the final condition $\mathcal{V}(x, T) = \varphi(x)$ in the sense given by Definition 3.2. Moreover, consider $(\varphi_n)_n$ a monotone increasing sequence of continuous functions, from \mathbb{R}^N to \mathbb{R} , pointwise converging to φ . For each $n \in \mathbb{N}$ we set $\mathcal{V}_n(x, \tau) := \inf_{a \in \mathcal{A}} \{\varphi_n(y_{x,\tau}^a(T))\}$. The proof will be divided in two steps.

Step 1. We first remark that by definition we have $\mathcal{V}_n(x, T) = \varphi_n(x)$, thus the final condition is fulfilled. Moreover, \mathcal{V}_n is the unique continuous solution of (3.27), with final condition $\mathcal{V}_n(\cdot, T) = \varphi_n(\cdot)$, in the sense of Definition 4.6. By the consistency result of Theorem 4.7, we get that \mathcal{V}_n is solution of (3.27) also in the sense of Definition 3.2.

Step 2. By using the same arguments as in [7], we can prove that \mathcal{V}_n converges pointwise to \mathcal{V} . Therefore, the conclusion follows from the stability with respect to the final condition proved in Theorem 4.10.

Furthermore, if assumption (3.31) is fulfilled, then we get the uniqueness result by using Theorem 4.11. \square

3.1 Numerical approximations of (3.27).

In the case when the Hamiltonian is continuous (both in time and in space), numerical discretization of Hamilton-Jacobi equations has been studied by many authors. The general framework of Barles-Souganidis [4] ensures that the numerical scheme is convergent (to the viscosity solution) whenever this scheme is consistent, monotone and stable and the HJB equation satisfies a strong comparison principle. The class of schemes satisfying these properties is very large and includes upwind finite differences, Semi-Lagrangian methods, Markov-Chain approximations.

In this section, we extend the result of [4] to the case of equation (3.27), where the Hamiltonian is only t -measurable, and show that the t -measurable viscosity notion is still a good framework to analyse the convergence of numerical approximations. We give also an example of a monotone, stable and consistent scheme of (3.27) based on finite differences approximations. Finally, a numerical example is given in Subsection 3.2.

Let G be a space grid on \mathbb{R}^N with a uniform mesh size $\Delta x > 0$ (of course a nonuniform grid could also be considered), and let $\Delta t > 0$ be a time step (we assume that $T/\Delta t$ belongs to \mathbb{N}). In the sequel, we will use the following notations:

$$\Delta := (\Delta x, \Delta t), \quad t_n := n\Delta t, \quad x_j \text{ is a node in } G, \quad N_T := \frac{T}{\Delta t} \quad (3.32)$$

Consider an approximation scheme of the following form:

$$\mathcal{S}^\Delta(t_n, x_j, v_j^n, v^{n+1}) = 0 \quad \forall x_j \in G, n = 0, \dots, N_T - 1; \quad v_j^{N_T} = \varphi(x_j) \quad \forall x_j \in G. \quad (3.33)$$

Thus if v is a continuous function defined on $[0, T] \times \mathbb{R}^N$, the approximation scheme reads

$$\mathcal{S}^\Delta(t, x, v(x, t), v(\cdot, t + \Delta t)) = 0 \text{ in } (0, T) \times \mathbb{R}^N. \quad (3.34)$$

On $\mathcal{S}^\Delta : (0, T) \times \mathbb{R}^N \times \mathbb{R} \times L^\infty(\mathbb{R}^N)$ we assume the following:

(M) Monotonicity. For each $u \geq v$ we have

$$\mathcal{S}^\Delta(t, x, r, u) \leq \mathcal{S}^\Delta(t, x, r, v) \quad \forall t \in (0, T), x \in \mathbb{R}^N, r \in \mathbb{R}. \quad (3.35)$$

(S) Stability. There exists $K > 0$ such that, if v^Δ is solution of (3.34) then

$$\|v^\Delta\|_{L^\infty} \leq K \|\varphi\|_{L^\infty}, \quad (3.36)$$

K being independent of $\Delta x, \Delta t$.

(C) Consistency. For every point (x_0, t_0) , for any $b \in L^1(0, T)$ and any function $\phi(x)$ such that: $\phi \in C^1(\mathbb{R}^N)$, by setting $\psi(x, t) := \int_0^t b(s) ds + \phi(x)$, we have:

$$\begin{aligned} \operatorname{ess\,sup}_{|t-t_0| \leq \Delta t} \sup_{x \in B_{\Delta x}(x_0), p \in B_{\Delta x}(D\phi(x_0))} \{-b(t) + H(t, x, p)\} &\geq \\ &\geq \mathcal{S}^\Delta(t_0, x_0, \psi(x_0, t_0), \psi(\cdot, t_0 + \Delta t)) + o_{\Delta x}(1) \geq \\ &\geq \operatorname{ess\,inf}_{|t-t_0| \leq \Delta t} \inf_{x \in B_{\Delta x}(x_0), p \in B_{\Delta x}(D\phi(x_0))} \{-b(t) + H(t, x, p)\}. \end{aligned} \quad (3.37)$$

An example of scheme fulfilling the above assumptions, when the Hamiltonian is given by (3.28), is the following

$$\begin{aligned} \mathcal{S}^\Delta(t, x, u(x, t), u(\cdot, t + \Delta t)) &:= \frac{u(x, t) - u(x, t + \Delta t)}{\Delta t} + \\ &+ \frac{1}{\Delta t} \int_t^{t+\Delta t} \sup_{a \in A} \left((-\mathcal{F})^+(s, x, a) \cdot \frac{u(x, t + \Delta t) - u(x - \Delta x, t + \Delta t)}{\Delta x} + \right. \\ &\quad \left. + (-\mathcal{F})^-(s, x, a) \cdot \frac{u(x + \Delta x, t + \Delta t) - u(x, t + \Delta t)}{\Delta x} \right) ds, \end{aligned} \quad (3.38)$$

where we classically denoted $g^+ := \max(g, 0)$ and $g^- := \min(g, 0)$.

Proposition 3.5. Assume that \mathcal{F} fulfils assumptions **(HF1)**-**(HF3)**, and consider the Hamiltonian in (3.28). Let $\Delta = (\Delta x, \Delta t)$ be mesh sizes satisfying:

$$\frac{\Delta t}{\Delta x} |\mathcal{F}(s, x, a)| ds \leq 1 \quad \text{for a.e } s \in (0, T), \forall x \in \mathbb{R}^N, a \in A. \quad (3.39)$$

Then, the scheme \mathcal{S}^Δ given in (3.38) satisfies conditions **(M)**, **(S)** and **(C)**.

Proof. First remark that the Stability condition **(S)** easily follows from the boundedness of \mathcal{F} and **(HF3)**. Moreover, the monotonicity **(M)** follows from condition (3.39) by standard arguments.

To prove consistency, we fix (x_0, t_0) and consider a function $\psi(x, t) = \int_0^t b(s) ds + \phi(x)$ for $b \in L^1(0, T)$ and $\phi \in C^1(\mathbb{R}^N)$. By using the regularity of ψ and assumption **(HF3)** on \mathcal{F} , we get:

$$\mathcal{S}^\Delta(t_0, x_0, \psi(x_0, t_0), \psi(\cdot, t_0 + \Delta t)) = \frac{1}{\Delta t} \int_{t_0}^{t_0 + \Delta t} \{-b(s) + H(s, x_0, D\phi(x_0))\} ds + o_{\Delta x}(1).$$

Condition **(C)** follows. \square

The general convergence result is the following.

Theorem 3.6. *Assume **(HF1)**-**(HF3)**. Let \mathcal{V} be defined as in (3.26) with φ fulfilling assumption **(Hid)**. Consider a sequence of continuous and bounded functions $\varphi_m : \mathbb{R}^N \rightarrow \mathbb{R}$ (for $m \geq 1$) such that $(\varphi_m)_{m \in \mathbb{N}}$ is monotone increasing and*

$$\lim_{m \rightarrow \infty} \varphi_m(x) = \varphi(x) \quad \forall x \in \mathbb{R}^N.$$

Let $\Delta = (\Delta x, \Delta t)$ be a mesh size such that the scheme \mathcal{S}^Δ fulfils conditions **(M)**, **(S)** and **(C)**, and let $v^{\Delta, m} := (v_j^n)_{n, j}$ be the solution of :

$$\mathcal{S}^\Delta(t_n, x_j, v_j^n, v^{n+1}) = 0 \quad \forall x_j \in G, n = 0, \dots, N_T - 1; \quad v_j^{N_T} = \varphi_m(x_j) \quad \forall x_j \in G. \quad (3.40)$$

Then, as $\Delta t \rightarrow 0$, $\Delta x \rightarrow 0$ and $m \rightarrow +\infty$, $v^{\Delta, m}$ converges pointwise to the function \mathcal{V} .

Proof. The proof will be given in two steps.

Step 1. We first suppose that the final data is continuous ($\varphi_m \equiv \varphi$). We consider a $\Delta_k = (\Delta x_k, \Delta t_k)$ and denote by v^{Δ_k} the solution of (3.40) corresponding to Δ_k and $\varphi_m \equiv \varphi$. We will prove that, as $k \rightarrow 0$, the sequence v^{Δ_k} converges locally uniformly to the unique L^1 -viscosity solution of (3.27).

For the sake of simplicity for each k we will set $(x_k, t_k) := (x_{j_k}, t_{n_k})$ where (x_{j_k}, t_{n_k}) are the point defined in (3.32) when Δ is Δ_k .

Let us first observe that by the stability assumption **(S)** the sequence v^{Δ_k} is bounded, therefore the following weak semi-limits are well defined:

$$v_*(x, t) := \liminf_{k \rightarrow 0} \lim_{x_k \rightarrow x, t_k \rightarrow t} v^{\Delta_k}(x_k, t_k) \quad v^*(x, t) := \limsup_{k \rightarrow 0} \lim_{x_k \rightarrow x, t_k \rightarrow t} v^{\Delta_k}(x_k, t_k). \quad (3.41)$$

Note that both v_* and v^* trivially satisfy the final condition in (3.27). Therefore, the convergence result will follow once we prove that v_* and v^* are respectively a L^1 -viscosity supersolution and a L^1 -viscosity subsolution of (3.27). Indeed, if this is true, by the comparison result [20, Theorem 8.1], we have $v^* \leq v_*$. Since the reverse is true by definition, the two weak semi limits coincide and the thesis follows.

Let us now prove that v^* is a L^1 -viscosity subsolution of (3.27). (The proof of v_* being a L^1 -viscosity supersolution of (3.27) is completely similar and will not be detailed.)

Following Definition 4.6 below, for any $b \in L^1(0, T)$, $\phi \in C^1(\mathbb{R}^N)$ and (x_0, t_0) local maximum point of $v^*(x, t) - \int_0^t b(s) ds - \phi(x)$ we have to prove that

$$\lim_{\delta \rightarrow 0^+} \operatorname{ess\,inf}_{|t-t_0| \leq \delta} \inf_{x \in B_\delta(x_0), p \in B_\delta(D\phi(x_0))} \{H(t, x, p) - b(t)\} \leq 0. \quad (3.42)$$

Note that, without loss of generality, we can assume that (x_0, t_0) is a *strict* local zero maximum of $v^*(x, t) - \int_0^t b(s)ds - \phi(x)$. There exists then a sequences of points (x_k, t_k) such that

- (a) $(x_k, t_k) \rightarrow (x_0, t_0)$ as $k \rightarrow 0$.
- (b) (x_k, t_k) is a local maximum point of $v^{\Delta_k}(x, t) - \int_0^t b(s)ds - \phi(x)$.
- (c) $\xi_k := v^{\Delta_k}(x_k, t_k) - \int_0^{t_k} b(s)ds - \phi(x_k) \rightarrow 0 = v^*(x_0, t_0) - \int_0^{t_0} b(s)ds - \phi(x_0)$ as $k \rightarrow 0$.

Thanks to (b), we can apply the monotonicity assumption **(M)** with $v = v^{\Delta_k}$, $u = \phi(x) + \int_0^t b(s)ds + \xi_k$ and $r = v^{\Delta_k}(x_k, t_k) = \xi_k + \phi(x_k) + \int_0^{t_k} b(s)ds$ and obtain

$$\begin{aligned} \mathcal{S}^{\Delta_k} \left(t_k, x_k, \xi_k + \phi(x_k) + \int_0^{t_k} b(s)ds, \xi_k + \phi(\cdot) + \int_0^{t_k + \Delta t_k} b(s)ds \right) &\leq \\ &\leq \mathcal{S}^{\Delta_k}(t_k, x_k, v^{\Delta_k}(x_k, t_k), v^{\Delta_k}(\cdot, t_k + \Delta t_k)) = 0, \end{aligned} \quad (3.43)$$

where we also used that v^{Δ_k} is a solution of (3.33).

Fix now a $\delta > 0$, by (a) and the regularity of ϕ we can always find a $\delta_k \leq \delta$ such that $\min(\Delta x_k, \Delta t_k) \leq \delta_k$, $B_{\delta_k}(t_k, x_k) \subseteq B_\delta(x_0, t_0)$, and $B_{\delta_k}(D\phi(x_k)) \subseteq B_\delta(D\phi(x_0))$. Therefore, also by the Consistency assumption **(C)** and (3.43) we have:

$$\begin{aligned} \operatorname{ess\,inf}_{|t-t_0| \leq \delta} \inf_{x \in B_\delta(x_0), p \in B_\delta(D\phi(x_0))} \{H(t, x, p) - b(t)\} &\leq \\ &\leq \operatorname{ess\,inf}_{|t-t_k| \leq \delta_k} \inf_{x \in B_{\delta_k}(x_k), p \in B_{\delta_k}(D\phi(x_k))} \{H(t, x, p) - b(t)\} \leq \\ &\leq \mathcal{S}^{\Delta_k} \left(t_k, x_k, \xi_k + \phi(x_k) + \int_0^{t_k} b(s)ds, \xi_k + \phi(\cdot) + \int_0^{t_k + \Delta t_k} b(s)ds \right) + o_{\delta_k}(1) \leq o_{\delta_k}(1). \end{aligned} \quad (3.44)$$

Inequality (3.42) follows then by letting $\delta \rightarrow 0^+$ (which implies $\delta_k \rightarrow 0^+$).

Step 2. For every $m \geq 1$, by Step 1, as $k \rightarrow 0$, the sequence $(v^{\Delta_k, m})_k$ converges to v_m the unique L^1 -viscosity solution of

$$\begin{cases} -v_t(x, t) + H(t, x, Dv) = 0 & \text{in } \mathbb{R}^N \times (0, T) \\ v(x, T) = \varphi_m(x) & \text{in } \mathbb{R}^N. \end{cases} \quad (3.45)$$

With the same arguments as in Step 1 of the proof of Theorem 3.4, we conclude the pointwise convergence of v_m to \mathcal{V} . \square

Remark 3.7. *In the case of Eikonal equation with t -measurable velocity function, a similar convergence result is proved, in the recent work of A. Monteillet [22], for a particular numerical scheme.*

3.2 A numerical test.

In this section, we use the scheme given in (3.38) to solve Hamilton-Jacobi equations coming from a simple control problem with BV trajectories.

Consider the target $\mathcal{C} := B(0, r)$, which is the ball centred at the origin and of radius $r = 0.25$. Consider also a trajectory $Y_{\tau X}^{(\alpha, c)}$, depending on the control variables $\alpha : (0, T) \rightarrow A := [0, 2\pi]$ and

$c : (0, T) \rightarrow U$, and governed by the following dynamics

$$\begin{aligned}\dot{Y}(t) &= c(t) \begin{pmatrix} \cos(\alpha) \\ \sin(\alpha) \end{pmatrix} + C_1 \begin{pmatrix} 1 \\ 1 \end{pmatrix} \delta_1 + C_2 \begin{pmatrix} 0 \\ 1 \end{pmatrix} \delta_2, \\ Y(\tau) &= X\end{aligned}$$

where $C_1 := 0.5$, $C_2 := 0.2$, and δ_u (for $u = 1, 2$) denotes the Dirac measure at time $t = u$. The control variable c takes its values in a compact set U . Here we will consider two cases:

- **Case 1:** $U \equiv \{0.5\}$ which amounts saying that we are allowed to move in any direction in the sphere centred at the origin and with radius 0.5.
- **Case 2:** $U = [0, 0.5]$, which means that we can move in any direction in the Ball centred at the origin and with radius 0.5.

In both cases, at time $t = 1$ and $t = 2$ the trajectories jump. We consider the value function corresponding to the *Rendez-Vous* problem:

$$v(t, X) := \inf\{\varphi(Y_{\tau, X}^{\alpha, c}(T)); \alpha \in L^\infty(0, T; A), c \in L^\infty(0, T; U)\},$$

where $T = 3$, and $\varphi(x) = 0$ when $x \in \mathcal{C}$ and 1 otherwise.

It is not difficult to compute the parametrized function:

$$\Phi(s) = \begin{cases} (15s, 0, 0) & 0 \leq s \leq \frac{1}{15}; \\ (1, \frac{15}{6}s - \frac{1}{6}, 0) & \frac{1}{15} < s < \frac{7}{15}; \\ (15s - 6, 1, 0) & \frac{7}{15} < s < \frac{8}{15}; \\ (2, 1, \frac{15}{6}s - \frac{8}{6}) & \frac{8}{15} < s < \frac{14}{15}; \\ (15s - 12, 2, 1) & \frac{14}{15} < s < 1. \end{cases}$$

Let us notice that in Case 2, the value function \bar{v} corresponding to the parametrized problem is lsc.

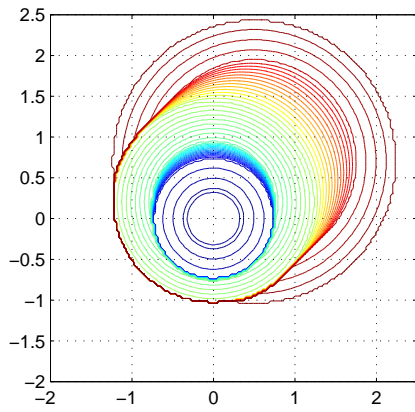
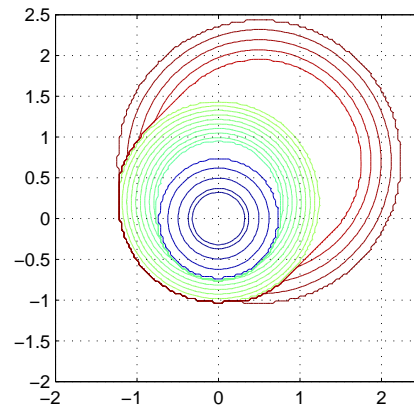
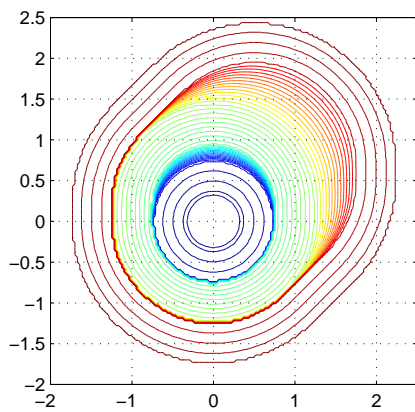
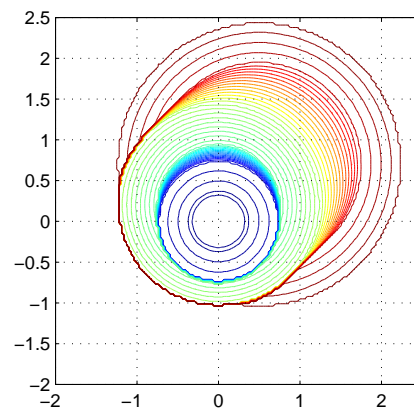
Fig. 1 shows the numerical solution in the Case 1, while Fig.2 shows the results corresponding to Case 2. These numerical experiments are performed by using the finite differences scheme with 150^2 grid points. Computations are done on the domain $[-1.5, 3]^2$. The final cost function is approximated by a function (with $n = 10$):

$$\varphi_n(X) := 1/n \min(1, \|x\| - 0.5). \quad (3.46)$$

In the two cases, we compute first the value function \bar{v} corresponding to the parametrized control problem, and then we deduce the original value function by using a change of variable. The latter step is very easy to perform numerically, since v turns to be just the restriction of \bar{v} on $[0, \frac{1}{15}] \cap [\frac{7}{15}, \frac{8}{15}] \cap [\frac{14}{15}, 1]$. In Figs. 1 & 2, we plot only the 0-level sets.

4 Properties of the L^1 -bilateral viscosity solution of HJB equations.

This section is devoted to the main properties of the L^1 -bilateral solutions we have defined in Definition 3.2. First, we give an equivalent formulation of this definition and we prove that it

(a) 0-level sets of \bar{v} (b) 0-level sets of v Figure 1: Case 1: Numerical solutions with 150^2 grid nodes.(a) 0-level sets of \bar{v} (b) 0-level sets of v Figure 2: Case 2: Numerical solutions with 150^2 grid nodes.

is consistent with the definitions of viscosity solutions given for a more regular HJB equation (Subsection 4.1). The Stability results are given in Subsection 4.2.

Fix $T > 0$, and consider the general Hamilton-Jacobi-Bellman equation

$$\begin{cases} -u_t(x, t) + H(t, x, Du) = 0 & \text{in } \mathbb{R}^N \times (0, T) \\ u(x, T) = \varphi(x) & \text{in } \mathbb{R}^N. \end{cases} \quad (4.47)$$

On the Hamiltonian $H : \mathbb{R}^+ \times \mathbb{R}^N \times \mathbb{R}^N \rightarrow \mathbb{R}$ we assume the following:

(H0) The function $H(t, x, p)$ is measurable in t and continuous in x and p . Moreover, for each $(x, p) \in \mathbb{R}^N \times \mathbb{R}^N$ we have $H(\cdot, x, p) \in L^1(\mathbb{R}^+)$.

(H1) For each compact subset K of $\mathbb{R}^N \times \mathbb{R}^N$ there exists a modulus $m = m(K) : (0, T) \times \mathbb{R}^+ \rightarrow \mathbb{R}^+$ such that $t \rightarrow m(t, r) \in L^1(0, T)$ for all $r \geq 0$, $m(t, r)$ is increasing in r , $m(\cdot, r) \rightarrow 0$ in $L^1(0, T)$ as $r \rightarrow 0$, and

$$|H(t, x, p) - H(t, y, q)| \leq m(t, |x - y| + |p - q|)$$

for almost every t and for any $(x, p), (y, q) \in K$.

Moreover:

(H2) There exists a function $k_0 \in L^\infty(\mathbb{R}^+; \mathbb{R}^+)$ such that

$$|H(t, x, p) - H(t, y, p)| \leq k_0(t)(1 + |p|)(|x - y|) \quad \text{for all } p \in \mathbb{R}^N, t \in \mathbb{R}^+, x, y \in \mathbb{R}^N.$$

(H3) For each (t, x) the function $H(t, x, \cdot)$ is convex and there exists a constant $L > 0$ such that

$$|H(t, x, p) - H(t, x, q)| \leq L|p - q| \quad \text{for all } p, q \in \mathbb{R}^N, t \in \mathbb{R}^+, x \in \mathbb{R}^N.$$

On the final data we suppose:

(Hid) The function $\varphi : \mathbb{R}^N \rightarrow \mathbb{R}$ is lower semi continuous and bounded.

Remark 4.1. *It is easy to check that if the dynamics \mathcal{F} fulfils assumptions **(HF1)**-**(HF3)**, then the Hamiltonian defined in (3.28) satisfies assumptions **(H0)**-**(H3)**.*

In order to give an equivalent formulation of the definition of L^1 -bilateral viscosity solution we need to introduce the following sets of functions. Fix (x_0, t_0) and a function $\phi \in C^1(\mathbb{R}^N \times \mathbb{R}^+)$ we set

$$\begin{aligned} \mathcal{H}^-(t_0, x_0, D\phi(x_0, t_0)) &:= \\ &= \{G(t, x, p) \in C(\mathbb{R}^+ \times \mathbb{R}^N \times \mathbb{R}^N), \text{ convex in } p, b(t) \in L^1(\mathbb{R}^+) \\ &\quad \text{such that } G(t, x, p) + b(t) \leq H(t, x, p) \\ &\quad \text{for all } x \in B_\delta(x_0), p \in B_\delta(D\phi(x_0, t_0)), \text{ a. e. } t \in B_\delta(t_0) \text{ and some } \delta > 0\} \end{aligned}$$

$$\begin{aligned} \mathcal{H}^+(t_0, x_0, D\phi(x_0, t_0)) &:= \\ &= \{G(t, x, p) \in C(\mathbb{R}^+ \times \mathbb{R}^N \times \mathbb{R}^N), \text{ convex in } p, b(t) \in L^1(\mathbb{R}^+) \\ &\quad \text{such that } G(t, x, p) + b(t) \geq H(t, x, p) \\ &\quad \text{for all } x \in B_\delta(x_0), p \in B_\delta(D\phi(x_0, t_0)), \text{ a. e. } t \in B_\delta(t_0) \text{ and some } \delta > 0\} \end{aligned}$$

Definition 4.2. L^1 -bilateral viscosity solution (L1Bvs) II

Let $u : \mathbb{R}^N \times \mathbb{R}^+ \rightarrow \mathbb{R}$ be a bounded lower semi-continuous function. We say that u is a L^1 -bilateral viscosity solution (L1Bvs) of (4.47) if:

1. for any (x_0, t_0) , $\phi \in C^1(\mathbb{R}^N \times \mathbb{R}^+)$, $(G, b) \in \mathcal{H}^-(t_0, x_0, D\phi(x_0, t_0))$ such that (x_0, t_0) is a local minimum point for $u(x, t) - \int_0^t b(s)ds - \phi(x, t)$ we have

$$-\phi_t(x_0, t_0) + G(t_0, x_0, D\phi(x_0, t_0)) \leq 0, \quad (4.48)$$

2. for any (x_0, t_0) , $\phi \in C^1(\mathbb{R}^N \times \mathbb{R}^+)$, $(G, b) \in \mathcal{H}^+(t_0, x_0, D\phi(x_0, t_0))$ such that (x_0, t_0) is a local minimum point for $u(x, t) - \int_0^t b(s)ds - \phi(x, t)$ we have

$$-\phi_t(x_0, t_0) + G(t_0, x_0, D\phi(x_0, t_0)) \geq 0. \quad (4.49)$$

Moreover, the final condition is satisfied in the following sense:

$$\varphi(x) = \inf \left\{ \liminf_{n \rightarrow \infty} u(x_n, t_n) : x_n \rightarrow x, t_n \uparrow T \right\}.$$

Remark 4.3. Note that in fact, there are many more formulations. We can take the test function $\phi(x, t) \in C^1(\mathbb{R}^N \times (0, T))$, (i.e. C^1 -depending also on t in Definition 3.2) and $\phi \in C^1(\mathbb{R}^N)$, (i.e. depending only on the x -variable) in Definition 4.2.

We can replace $\phi \in C^1(\mathbb{R}^N)$ by $\phi \in C^2(\mathbb{R}^N), \dots, C^\infty(\mathbb{R}^N)$. Moreover, by classical arguments in the theory of viscosity solutions, we may replace the local minimum by global, or local strict or global strict.

Proposition 4.4. Assume (H0) and (H1). Then, Definition 3.2 and Definition 4.2 are equivalent.

Proof. We first remark that for any $b \in L^1(0, T)$, $\phi \in C^1(\mathbb{R}^N)$ and (x_0, t_0) local minimum point for $u(x, t) - \int_0^t b(s)ds - \phi(x)$ we have

$$\begin{aligned} \lim_{\delta \rightarrow 0^+} \operatorname{ess\,sup}_{|t-t_0| \leq \delta} \sup_{x \in B_\delta(x_0), p \in B_\delta(D\phi(x_0))} \{H(t, x, p) - b(t)\} &= \\ &= \inf_{(G, b) \in \mathcal{H}^+(t_0, x_0, D\phi(x_0))} G(t_0, x_0, D\phi(x_0)) \end{aligned}$$

and

$$\begin{aligned} \lim_{\delta \rightarrow 0^+} \operatorname{ess\,inf}_{|t-t_0| \leq \delta} \inf_{x \in B_\delta(x_0), p \in B_\delta(D\phi(x_0))} \{H(t, x, p) - b(t)\} &= \\ &= \sup_{(G, b) \in \mathcal{H}^-(t_0, x_0, D\phi(x_0))} G(t_0, x_0, D\phi(x_0)). \end{aligned}$$

The equivalence of the two definitions follows then by observing that in Definition 4.2 we can consider test functions ϕ depending only on the x -variable. (See also Remark 4.3.)

□

4.1 Consistency

We prove now that our definition is consistent with the definitions of viscosity solutions given for a more regular HJB equation. In particular we consider the case of a time-continuous Hamiltonian and/or a continuous initial data. For the sake of completeness let us recall here the definition of viscosity solution in those cases.

Definition 4.5 (bilateral viscosity solution (Bvs), See [6]). *Assume that H is continuous w.r. to the time variable. Let $u \in LSC(\mathbb{R}^N \times (0, T))$ be a bounded function. We say that u is a bilateral viscosity solution (Bvs) of (4.47) if:*
for any $\phi \in C^1(\mathbb{R}^N \times (0, T))$ and (x_0, t_0) local minimum point of $u(x, t) - \phi(x, t)$ we have

$$-\phi_t(x_0, t_0) + H(t_0, x_0, D\phi(x_0, t_0)) = 0.$$

Moreover, the final condition is satisfied in the following sense:

$$\varphi(x) = \inf \left\{ \liminf_{n \rightarrow \infty} u(x_n, t_n) : x_n \rightarrow x, t_n \uparrow T \right\}$$

Definition 4.6 (L^1 -viscosity solution (L1vs), [20, 21]). *Assume that the final condition φ is a continuous function on \mathbb{R}^N .*

We say that $u \in LSC(\mathbb{R}^N \times (0, T))$ is a L^1 -viscosity supersolution (L1vsp) of (4.47) if: for any $b \in L^1(0, T)$, $\phi \in C^1(\mathbb{R}^N)$ and (x_0, t_0) local minimum point of $u(x, t) - \int_0^t b(s)ds - \phi(x)$ we have

$$\lim_{\delta \rightarrow 0^+} \operatorname{ess\,sup}_{|t-t_0| \leq \delta} \sup_{x \in B_\delta(x_0), p \in B_\delta(D\phi(x_0))} \{H(t, x, p) - b(t)\} \geq 0.$$

We say that $u \in USC(\mathbb{R}^N \times (0, T))$ is a L^1 -viscosity subsolution (L1vsb) of (4.47) if: for any $b \in L^1(0, T)$, $\phi \in C^1(\mathbb{R}^N)$ and (x_0, t_0) local maximum point of $u(x, t) - \int_0^t b(s)ds - \phi(x)$ we have

$$\lim_{\delta \rightarrow 0^+} \operatorname{ess\,inf}_{|t-t_0| \leq \delta} \inf_{x \in B_\delta(x_0), p \in B_\delta(D\phi(x_0))} \{H(t, x, p) - b(t)\} \leq 0.$$

We say that $u \in C(\mathbb{R}^N \times (0, T))$ is a L^1 -viscosity solution (L1vs) if it is both a L^1 -viscosity subsolution and a L^1 -viscosity supersolution and the final condition is satisfied pointwise:

$$u(x, T) = \varphi(x) \text{ in } \mathbb{R}^N.$$

Theorem 4.7. (Consistency). *Assume (H0)-(H3) and (Hid).*

(a) *If the final condition φ is a continuous function, then*

$$u \text{ is a } L^1\text{-bilateral viscosity solution} \iff u \text{ is a } L^1\text{-viscosity solution.}$$

(b) *If the Hamiltonian H is continuous also in the t -variable, then*

$$u \text{ is a } L^1\text{-bilateral viscosity solution} \iff u \text{ is a bilateral viscosity solution.}$$

Proof of (a).

The key tool to prove this equivalence is a Lemma introduced in the [6] to prove the equivalence between a Bvs and a Cvs. For the sake of completeness we recall here this result.

Lemma 4.8. [6, Theorem 1.1] *Let W be a continuous function on $[0, \infty) \times \mathbb{R}^n$ such that W has a zero maximum (minimum) at (τ, ξ) . Let $\varepsilon > 0$. Then there is a smooth function ψ , a finite set of numbers $\alpha_k \geq 0$ summing to one, and a finite collection of points (t_k, x_k) such that*

1. $W - \psi$ has a zero minimum (maximum) at (t_k, x_k) ;
2. $(t_k, x_k) \in B_{o_\varepsilon(1)\sqrt{\varepsilon}}(s, y)$ for some $(s, y) \in B_{o_\varepsilon(1)}(\tau, \xi)$;
3. $|D_{t,x}\psi(t_k, x_k)| = \frac{o_\varepsilon(1)}{\sqrt{\varepsilon}}$;
4. $\sum_k \alpha_k D_{t,x}\psi(t_k, x_k) = 0$.

Proof of u is a L1vs $\Rightarrow u$ is a L1Bvs.

Following Definition 3.2 we have to show that fix $b \in L^1(0, T)$, $\phi \in C^1(\mathbb{R}^N)$ and (x_0, t_0) local minimum point for $u(x, t) - \int_0^t b(s)ds - \phi(x)$ we have

$$\lim_{\delta \rightarrow 0^+} \operatorname{ess\,sup}_{|t-t_0| \leq \delta} \sup_{x \in B_\delta(x_0), p \in B_\delta(D\phi(x_0))} \{H(t, x, p) - b(t)\} \geq 0 \quad (4.50)$$

and

$$\lim_{\delta \rightarrow 0^+} \operatorname{ess\,inf}_{|t-t_0| \leq \delta} \inf_{x \in B_\delta(x_0), p \in B_\delta(D\phi(x_0))} \{H(t, x, p) - b(t)\} \leq 0. \quad (4.51)$$

Since u is a L1vs, in particular is a L^1 -viscosity supersolution therefore inequality (4.50) is satisfied. To prove (4.51), for each $\delta > 0$ we apply Lemma 4.8 above choosing ε small enough the ensure the existence of an $\eta > 0$ such that $\frac{o_\varepsilon(1)}{\sqrt{\varepsilon}} + o_\varepsilon(1) + \eta \leq \delta$ and $o_\varepsilon(1)\sqrt{\varepsilon} + o_\varepsilon(1) + \eta \leq \delta$ (and with $W(t, x) = u(x, t) + \int_0^t b(s)ds - \phi(x, t)$).

Therefore, there exists a smooth function ψ and a finite set of points (x_k, t_k) such that $u - \int_0^t b - (\phi + \psi)$ has a zero maximum at (x_k, t_k) and for each k

$$B_\eta(x_k, t_k) \subset B_\delta(t_0, x_0), \quad B_\eta(D\phi(x_k) + D\psi(x_k, t_k)) \subset B_\delta(D\phi(x_0)). \quad (4.52)$$

Thus

$$\begin{aligned} \operatorname{ess\,inf}_{|t-t_0| \leq \delta} \inf_{x \in B_\delta(x_0), p \in B_\delta(D\phi(x_0))} \{H(t, x, p) - b(t)\} &\leq \\ &\leq \operatorname{ess\,inf}_{|t-t_k| \leq \eta} \inf_{x \in B_\eta(x_k), p \in B_\eta(D\phi(x_k) + D\psi(x_k, t_k))} \{H(t, x, p) - b(t)\}. \end{aligned} \quad (4.53)$$

Since u is a L1vs, in particular is a L^1 -viscosity subsolution therefore in each point (t_k, x_k) we have

$$\lim_{\eta \rightarrow 0^+} \operatorname{ess\,inf}_{|t-t_k| \leq \eta} \inf_{x \in B_\eta(x_k), p \in B_\eta(D\phi(x_k) + D\psi(x_k, t_k))} \{H(t, x, p) - b(t)\} \leq 0.$$

Letting δ going to 0^+ ($\Rightarrow \eta \rightarrow 0^+$) in (4.53) we obtain (4.51) and conclude the proof.

Proof of u is a L1Bvs $\Rightarrow u$ is a L1vs.

We first remark that, by Definition 3.2 if u is a L1Bvs, is in particular a L^1 -viscosity supersolution. Therefore, to prove that u is a L^1 -viscosity subsolution fix $b \in L^1(0, T)$, $\phi \in C^1(\mathbb{R}^N)$ and (x_0, t_0) local maximum point of $u(x, t) - \int_0^t b(s)ds - \phi(x)$ our thesis is

$$\lim_{\delta \rightarrow 0^+} \operatorname{ess\,inf}_{|t-t_0| \leq \delta} \inf_{x \in B_\delta(x_0), p \in B_\delta(D\phi(x_0))} \{H(t, x, p) - b(t)\} \leq 0. \quad (4.54)$$

As above, for each $\delta > 0$ we apply Lemma 4.8 choosing ε small enough to ensure the existence of an $\eta > 0$ such that $\frac{o_\varepsilon(1)}{\sqrt{\varepsilon}} + o_\varepsilon(1) + \eta \leq \delta$ and $o_\varepsilon(1)\sqrt{\varepsilon} + o_\varepsilon(1) + \eta \leq \delta$, and with $W(t, x) = u(x, t) + \int_0^t b(s)ds - \phi(x, t)$. Therefore, there exists a smooth function ψ and a finite set of points (x_k, t_k) such that $u - \int_0^t b - (\phi + \psi)$ has a zero minimum at (x_k, t_k) and for each k

$$B_\eta(x_k, t_k) \subset B_\delta(t_0, x_0), \quad B_\eta(D\phi(x_k) + D\psi(x_k, t_k)) \subset B_\delta(D\phi(x_0)). \quad (4.55)$$

Thus,

$$\begin{aligned} \operatorname{ess\,inf}_{|t-t_0| \leq \delta} \inf_{x \in B_\delta(x_0), p \in B_\delta(D\phi(x_0))} \{H(t, x, p) - b(t)\} &\leq \\ &\leq \operatorname{ess\,inf}_{|t-t_k| \leq \eta} \inf_{x \in B_\eta(x_k), p \in B_\eta(D\phi(x_k) + D\psi(x_k, t_k))} \{H(t, x, p) - b(t)\}. \end{aligned} \quad (4.56)$$

Since u is a L1Bvs we have (3.30) at each point (t_k, x_k) , i.e.

$$\lim_{\eta \rightarrow 0^+} \operatorname{ess\,inf}_{|t-t_k| \leq \eta} \inf_{x \in B_\eta(x_k), p \in B_\eta(D\phi(x_k) + D\psi(x_k, t_k))} \{H(t, x, p) - b(t)\} \leq 0.$$

Letting δ going to 0^+ ($\Rightarrow \eta \rightarrow 0^+$) in (4.56) we obtain (4.54) and conclude the proof.

Proof of (b).

Proof of u is a L1Bvs $\Rightarrow u$ is a Bvs.

Thanks to the continuity of H for any $\phi \in C^1(\mathbb{R}^N \times \mathbb{R}^+)$ and (x_0, t_0) local minimum point of $u(x, t) - \phi(x, t)$ we can choose $G = H$ and $b \equiv 0$ in Definition 4.2. Since the couple $(H, 0)$ is in both $\mathcal{H}^-(t_0, x_0, D\phi(x_0, t_0))$ and $\mathcal{H}^+(t_0, x_0, D\phi(x_0, t_0))$ the two inequalities (4.49) and (4.48) are fulfilled. Therefore

$$-\phi_t(x_0, t_0) + H(t_0, x_0, D\phi(x_0, t_0)) = 0$$

and the thesis follows.

Proof of u is a Bvs $\Rightarrow u$ is a L1Bvs.

Fix $b \in L^1(0, T)$, $\phi \in C^1(\mathbb{R}^N)$ and (x_0, t_0) local minimum point of $u(x, t) - \int_0^t b(s)ds - \phi(x)$. By standard mollification's arguments we can approximate b in $L^1(0, T)$ by a sequence $(b_\varepsilon)_{\varepsilon > 0} \in C^\infty((0, T))$ and we have the existence of a sequence of points $(x_\varepsilon, t_\varepsilon)$ such that as $\varepsilon \rightarrow 0$, $(x_\varepsilon, t_\varepsilon) \rightarrow (x_0, t_0)$ and fix ε , $(x_\varepsilon, t_\varepsilon)$ is a local minimum point for $u(x, t) + \int_0^t b_\varepsilon(s)ds - \phi(x)$. Since u is a Bvs we have

$$-b_\varepsilon(t_\varepsilon) + H(t_\varepsilon, x_\varepsilon, D\phi(x_\varepsilon)) = 0.$$

Note that for each $\delta > 0$ fixed we can find an ε small enough to have

$$\operatorname{ess\,inf}_{|t-t_0| \leq \delta} \inf_{x \in B_\delta(x_0), p \in B_\delta(D\phi(x_0))} \{H(t, x, p) - b(t)\} \leq -b_\varepsilon(t_\varepsilon) + H(t_\varepsilon, x_\varepsilon, D\phi(x_\varepsilon)) = 0$$

and

$$0 = -b_\varepsilon(t_\varepsilon) + H(t_\varepsilon, x_\varepsilon, D\phi(x_\varepsilon)) \leq \operatorname{ess\,sup}_{|t-t_0| \leq \delta} \sup_{x \in B_\delta(x_0), p \in B_\delta(D\phi(x_0))} \{H(t, x, p) - b(t)\}.$$

Therefore, letting $\delta \rightarrow 0$, we respectively obtain (3.30) and (3.29) and this ends the proof. \square

4.2 Stability

We will prove here the stability with respect to the final datum and the one with respect to the Hamiltonian. The latest will be proved under a very weak convergence in time that as been proved for L^1 -viscosity solution by Barles in [3]. (Our proof is indeed an adaptation to L1Bvs of the proof of [3, Theorem 1.1]). Note that in this proof we only need assumptions **(H0)**-**(H1)** on the Hamiltonian.

Theorem 4.9. Stability w.r.to H . For each $n \in \mathbb{N}$ let u_n be a L^1 -bilateral viscosity solution of

$$\begin{cases} -u_t(x, t) + H_n(t, x, Du) = 0 & \text{in } \mathbb{R}^N \times (0, T) \\ u(x, T) = \varphi(x) & \text{in } \mathbb{R}^N. \end{cases} \quad (4.57)$$

We assume that:

- I) For each $n \in \mathbb{N}$ the Hamiltonian H_n fulfils hypotheses **(H0)**-**(H1)** for some modulus $m_n = m_n(K)$ such that $\|m_n(\cdot, r)\|_{L^1(0, T)} \rightarrow 0$ as $r \rightarrow 0$ uniformly with respect to n , for any compact subset K .
- II) There exists a function H fulfilling hypotheses **(H0)**-**(H1)** such that, for any $(x, p) \in \mathbb{R}^N \times \mathbb{R}^N$,

$$\lim_{n \rightarrow \infty} \int_0^t H_n(s, x, p) ds \rightarrow \int_0^t H(s, x, p) ds \text{ locally uniformly in } (0, T).$$

- III) The final condition φ fulfils **(Hid)**,

Then the function

$$u(x, t) := \inf_{(x_n, t_n) \rightarrow (x, t)} \liminf_{n \rightarrow \infty} u_n(x_n, t_n),$$

is a L^1 -bilateral viscosity solution of

$$\begin{cases} -u_t(x, t) + H(t, x, Du) = 0 & \text{in } \mathbb{R}^N \times (0, T) \\ u(x, T) = \varphi(x) & \text{in } \mathbb{R}^N. \end{cases} \quad (4.58)$$

Proof. Following Definition 4.2 we have to prove that

1. for any (x_0, t_0) , $\phi \in C^1(\mathbb{R}^N \times \mathbb{R}^+)$, $(G, b) \in \mathcal{H}^-(t_0, x_0, D\phi(x_0, t_0))$ such that (x_0, t_0) is a local minimum point for $u(x, t) - \int_0^t b(s) ds - \phi(x, t)$ we have

$$-\phi_t(x_0, t_0) + G(t_0, x_0, D\phi(x_0, t_0)) \leq 0, \quad (4.59)$$

2. for any (x_0, t_0) , $\phi \in C^1(\mathbb{R}^N \times \mathbb{R}^+)$, $(G, b) \in \mathcal{H}^+(t_0, x_0, D\phi(x_0, t_0))$ such that (x_0, t_0) is a local minimum point for $u(x, t) - \int_0^t b(s) ds - \phi(x, t)$ we have

$$-\phi_t(x_0, t_0) + G(t_0, x_0, D\phi(x_0, t_0)) \geq 0. \quad (4.60)$$

In order to prove 1, let us fix a (x_0, t_0) , $\phi \in C^1(\mathbb{R}^N \times \mathbb{R}^+)$, $(G, b) \in \mathcal{H}^-(t_0, x_0, D\phi(x_0, t_0))$ such that (x_0, t_0) is a *strict* local minimum point for $u(x, t) - \int_0^t b(s) ds - \phi(x, t)$.

Fix now a small $\delta > 0$, we consider a large compact subset K of $\mathbb{R}^N \times \mathbb{R}^N$ and the functions m, m_n given by assumptions I), II). We construct a new sequence $(u_n^\delta)_n$ defined by

$$u_n^\delta(x, t) := u_n(x, t) + \int_0^t [m_n(s, \delta) + m(s, \delta)] ds.$$

Note that for each n, δ the function u_n^δ is a L1Bvs of

$$-w_t + H_n(t, x, Dw) - m_n(t, \delta) - m(t, \delta) = 0. \quad (4.61)$$

Moreover, if we set $u^\delta(x, t) := \inf_{(x_n, t_n) \rightarrow (x, t)} \liminf_{n \rightarrow \infty} u_n^\delta(x_n, t_n)$, by the properties of m, m_n we have $u \leq u^\delta \leq u + O_\delta(1)$. Therefore, by classical results, since (x_0, t_0) is a *strict* local minimum point of $u(x, t) - \int_0^t b(s) ds - \phi(x, t)$, for δ small enough there exists a local minimum point of $u^\delta(x, t) - \int_0^t b(s) ds - \phi(x, t)$, that we will denote (x_δ, t_δ) . Note that $(x_\delta, t_\delta) \rightarrow (x_0, t_0)$ as $\delta \rightarrow 0$.

We set now

$$\psi_n(s) := H_n(s, x_\delta, D\phi(x_\delta, t_\delta)) - H(s, x_\delta, D\phi(x_\delta, t_\delta)).$$

Our aim is to use the fact that the function u_n^δ is a L1Bvs of (4.61) by testing with the function $\phi(x, t) + \int_0^t b - \int_0^t \psi_n$. To do this we first observe that the convergence assumption II) implies $\int_0^t \psi_n \rightarrow 0$ locally uniformly in $(0, T)$ therefore, for each (x_δ, t_δ) local minimum point of $u^\delta(x, t) - \int_0^t b(s) ds - \phi(x, t)$, there exists a sequence $(x_\delta^n, t_\delta^n) \rightarrow (x_\delta, t_\delta)$ as $n \rightarrow \infty$ of local minimum points of $u_n^\delta(x, t) - \phi(x, t) - \int_0^t b(s) ds + \int_0^t \psi_n(s) ds$. (Recall that $u^\delta(x, t) := \inf_{(x_n, t_n) \rightarrow (x, t)} \liminf_{n \rightarrow \infty} u_n^\delta(x_n, t_n)$).

Let $(G, b) \in \mathcal{H}^-(t_0, x_0, D\phi(x_0, t_0))$ we state now that there exists a n big enough and a δ small enough such that we can find a $\eta > 0$ for which

$$\begin{aligned} \psi_n(t) + G(t, x, p) + b(t) &\geq H_n(t, x, p) - m_n(t, \delta) - m(t, \delta) \\ &\quad \forall t \in B_\eta(t_\delta^n), x \in B_\eta(x_\delta^n), p \in B_\eta(D\phi(x_\delta^n, t_\delta^n)). \end{aligned} \quad (4.62)$$

Indeed, since $(G, b) \in \mathcal{H}^-(t_0, x_0, D\phi(x_0, t_0))$ there exists a β such that

$$\begin{aligned} \psi_n(t) + G(t, x, p) + b(t) &\geq H_n(t, x, p) - m_n(t, \delta) - m(t, \delta) \\ &\quad \forall t \in B_\beta(t_0), x \in B_\beta(x_0), p \in B_\beta(D\phi(x_0, t_0)) \end{aligned}$$

(where we used also the definition of m, m_n .) Thus (4.62) follows from $(x_\delta^n, t_\delta^n) \rightarrow (x_\delta, t_\delta)$ as $n \rightarrow \infty$, $(x_\delta, t_\delta) \rightarrow (x_0, t_0)$ as $\delta \rightarrow 0$ and the regularity of ϕ .

By definition of L1Bvs, condition (4.62) and the fact that (x_δ^n, t_δ^n) is a local minimum point of $u_n^\delta(x, t) - \phi(x, t) - \int_0^t b(s) ds + \int_0^t \psi_n(s) ds$ imply that

$$-\phi_t(x_\delta^n, t_\delta^n) + G(x_\delta^n, t_\delta^n, D\phi(x_\delta^n, t_\delta^n)) \leq 0.$$

Therefore letting $n \rightarrow \infty$ and $\delta \rightarrow 0$ by the continuity of G we obtain (4.59) and conclude the proof of 1.

Point 2 can be proved with the same argument by remarking that the functions

$$u_n^\delta(x, t) := u_n(x, t) - \int_0^t [m_n(s, \delta) + m(s, \delta)] ds.$$

are L1Bvs of

$$-w_t + H_n(t, x, Dw) + m_n(t, \delta) + m(t, \delta) = 0.$$

□

Theorem 4.10. (Stability w.r.to φ .) For each $n \in \mathbb{N}$ let u_n be a L^1 -bilateral viscosity solution of equation (4.47) with final condition

$$u(x, T) = \varphi_n(x) \quad \text{in } \mathbb{R}^N.$$

Assume that, for each $n \in \mathbb{N}$, the function $\varphi_n \in C(\mathbb{R}^N)$ and is bounded, moreover the sequence $(\varphi_n)_{n \in \mathbb{N}}$ is monotone increasing and

$$\lim_{n \rightarrow \infty} \varphi_n(x) = \varphi(x) \quad \forall x \in \mathbb{R}^N.$$

Then, the function

$$u(x, t) := \lim_{n \rightarrow \infty} u_n(x, t),$$

is a L^1 -bilateral viscosity solution of equation (4.47) with final condition

$$u(x, T) = \varphi(x) \quad \text{in } \mathbb{R}^N.$$

Proof. By definition of L1BVs our we have to prove that $\forall x \in \mathbb{R}^N$,

$$\varphi(x) = \inf_{(x_n, t_n) \rightarrow (x, T)} \liminf_{n \rightarrow \infty} u(x_n, t_n).$$

Note that, since $\varphi_n \in C(\mathbb{R}^N)$, u_n is continuous in $\mathbb{R}^N \times [0, T]$ (see [20, Corollary 1.10]). Therefore, for each sequence $(x_n, t_n) \rightarrow (x, T)$, we have

$$\varphi(x) = \lim_{n \rightarrow \infty} \varphi_n(x) = \lim_{n \rightarrow \infty} u_n(x, T) = \lim_{n \rightarrow \infty} \lim_{n \rightarrow \infty} u_n(x_n, t_n) = \lim_{n \rightarrow \infty} u(x_n, t_n)$$

and the proof is completed. \square

4.3 Uniqueness

We finally prove the uniqueness result.

Theorem 4.11. Assume **(H0)**-**(H3)** and **(Hid)** If, moreover, there exists a continuous function $\omega : \mathbb{R}^+ \rightarrow \mathbb{R}$ such that $\omega(0) = 0$ and

$$|H(t, x, p) - H(s, x, p)| \leq \omega(|t - s|)|p| \quad \forall p \in \mathbb{R}^N, \forall x \in \mathbb{R}^N, \forall t, s \in \mathbb{R}^+ \quad (4.63)$$

then there exists at most one L^1 -bilateral viscosity solution of (4.47).

Proof. This proof will follow the idea of G.Barles of using the inf-convolution in the proof of uniqueness for bilateral viscosity solution [2, Theorem 5.14].

Suppose that there exist v and u two L^1 -bilateral viscosity solution of (4.47). Since v is in particular a L^1 -viscosity supersolution the main point is to look for a sequence of L^1 -viscosity subsolutions of (4.47) approximating u . The thesis will then follow by comparison result for L^1 -viscosity solution.

The construction of the approximating sequence can be summarised in the following Lemma. The proof being an adaptation of the proof given in [2, Lemme 5.5] will be not detailed (see also [5, Lemma 19]).

Lemma 4.12. *Under the assumption of Theorem 4.11, if u is L^1 -bilateral viscosity solution of (4.47), let u_ε be defined by*

$$u_\varepsilon(x, t) := \inf_{y \in \mathbb{R}^N} \left\{ u(y, t) + e^{-Kt} \frac{|x - y|^2}{\varepsilon^2} \right\}, \quad \varepsilon > 0.$$

Then, the upper semi continuous envelope $(u_\varepsilon)^$ is a L^1 -viscosity subsolution of*

$$-(u_\varepsilon)_t + H(t, x, Du_\varepsilon) - \|K\|_\infty e^{\frac{1}{2}KT} M\varepsilon = 0 \quad \text{for } (x, t) \in \mathbb{R}^N \times (0, T), \quad (4.64)$$

for K big enough and where $M = \sqrt{2} \|u\|_\infty$. Moreover,

$$(u_\varepsilon)^*(x, T) \leq \varphi(x) \quad \text{for } x \in \mathbb{R}^N. \quad (4.65)$$

Since $(u_\varepsilon)^*$ is a L^1 -viscosity subsolution of (4.64) the function $(u_\varepsilon)^* - \|K\|_\infty e^{\frac{1}{2}KT} M\varepsilon$ is a L^1 -viscosity subsolution of (4.47), therefore, by the comparison result for L^1 -viscosity solutions (see [20, Theorem 8.1] or [25]) we obtain

$$(u_\varepsilon)^* - \|K\|_\infty e^{\frac{1}{2}KT} M\varepsilon \leq v(x, t) \quad \forall (x, t) \in \mathbb{R}^N \times (0, T)$$

where we used also (4.65). Letting $\varepsilon \rightarrow 0$ we have

$$u(x, t) \leq v(x, t) \quad \forall (x, t) \in \mathbb{R}^N \times (0, T),$$

thus, reversing the roles of u and v , the uniqueness follows. \square

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