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The Pontryagin Maximum Principle in the Wasserstein Space

Benoît Bonnet, Francesco Rossi

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Abstract

We prove a Pontryagin Maximum Principle for optimal control problems in the space of probability measures, where the dynamics is given by a transport equation with non-local velocity.

We formulate this first-order optimality condition using the formalism of subdifferential calculus in Wasserstein spaces. We show that the geometric approach based on needle variations and on the evolution of the covector (here replaced by the evolution of a measure on the dual space) can be translated into this formalism.

1 Introduction

Transport equations with non-local interaction terms have been intensively studied for decades by various communities. They were for instance already introduced in statistical physics in 1938 when Vlasov proposed these equations to describe long-range Coulomb interactions [31]. For such reasons, several transport equations appear as mean-field limit of particle systems, see e.g. [26, 29]. More recently, the study of crowd modelling has stimulated a renewed interest for these equations. Indeed, pedestrians have a long-range perception of their space, and thus choose their path based on long-range interactions. While such interactions do not enjoy action-reaction properties which are typical in physical models, methods connected to mean-field limit approaches have shown their adaptability to this setting too. See e.g. [7, 14, 24, 25]. More generally, the study of other kind of interacting agents, such as opinion dynamics on networks [8, 23], or animal flocks [6, 15], has been studied with similar techniques.

Several contributions have shown that the natural setting for studying transport equations with non-local terms is the space of measures endowed with the Wasserstein distance, see e.g. [5]. In this case, existence and uniqueness of the solution of a Cauchy problem are ensured by a natural Lipschitz condition [4], and metric estimates for the associated flow are available too [27]. For simplicity, we will only deal with measures with compact support, for which the Wasserstein distance is always finite.

Beside the analysis of such partial differential equations, it is now of great interest to study **control problems for the transport equation with non-local velocities**. Beside few recent results about controllability [17], most of the contributions in this direction have considered optimal control problems, i.e. the minimization of a functional where the constraint is a controlled dynamics. Applications of these problems are of great interest, such as for the reduction of the escape time for a crowd [3, 19], or for enforcing consensus in an opinion network by minimizing the variance of the opinions (see e.g. [11, 12, 28]).

Existence of optimal controls has been investigated in [21], as well as in the setting of mean-field control [1, 2]. Convergence of optimizers via the mean-field limit of the dynamics was also studied with methods related to Γ -convergence in [20].

The next logical step in the derivation of first-order necessary optimality conditions allowing to characterize and compute optimal trajectories. While some few specific results were presented in [9], optimality conditions need a sufficiently rich differential structure, namely to compute derivatives of the functional to be minimized. In this setting, the state is represented by a measure, for which the adapted setting is given by subdifferential calculus in Wasserstein spaces. For a thorough introduction, see [5]. We recall the main useful results in Section 2.

Our contribution in this article is to show that, in this general setting, several results of geometric control can be translated from finite-dimensional dynamical systems to transport equations with non-local velocities. With this aim, we derive a new Pontryagin Maximum Principle in this infinite-dimensional setting. While the proof scheme is close to the classical finite-dimensional case, each step requires the definition of tools adapted to Wasserstein spaces.

As a result, the new Pontryagin Maximum Principle (PMP in the following) is formulated in the language of subdifferential calculus in Wasserstein spaces. In particular, the state-costate variables are here replaced by a measure on the cotangent bundle, that satisfies mixed boundary conditions. The dynamics is given by an Hamiltonian system in the space of measures, similar to what studied in [4]. The maximized Hamiltonian is given by maximization in an adapted space of controls, namely of functions satisfying Lipschitz constraints.

In this article, we then prove a PMP for optimal control problems given in the general form

$$(\mathcal{P}) \quad \begin{cases} \min_{u \in \mathcal{U}} \left[\int_0^T L(\mu(t), u(t)) dt + \varphi(\mu(T)) \right], \\ \text{s.t.} \begin{cases} \partial_t \mu(t) + \nabla \cdot ((v[\mu(t)])(t, \cdot) + u(t, \cdot))\mu(t) = 0, \\ \mu(0) = \mu^0 \in \mathcal{P}_c(\mathbb{R}^d). \end{cases} \end{cases} \quad (1)$$

As already stated, our formulation of the Pontryagin Maximum Principle deeply relies on the formalism of subdifferential calculus in Wasserstein spaces (see e.g. [5, 13, 22]). In this formalism, the *extended subdifferential* $\partial\phi(\mu)$ (see Definition 18 below) of a functional $\phi(\cdot)$ at a given measure $\mu \in \mathcal{P}_c(\mathbb{R}^d)$ is made of transport plans. As it is the case for subdifferential calculus in Banach spaces, there exists a notion of *minimal selection* (see Theorem 3 below) among the elements of this subdifferential. The minimal selection in an extended subdifferential, which we denote by $\partial^\circ\phi(\mu)$, plays the same conceptual role of the *gradient* of a differentiable functional. The existence of such minimal selection is a consequence of the *regularity* hypothesis (see Definition 19 and the corresponding Theorem 3 below), that we impose to the functionals studied in the following.

In this context, the *barycenter* $\tilde{\gamma}_\phi^\circ : \mathbb{R}^d \rightarrow \mathbb{R}^d$ (see Definition 16 below) of the minimal selection is the closest object to what would be a gradient in the sense of subdifferential calculus, in particular when computing derivatives along curves of measures (see Proposition 21 below). However, barycenters of extended subdifferentials are not in the *classical subdifferentials* in general. Yet for a good score of functionals involved in applications such as potential and interaction energies, relative entropies, variance functionals (see Section 1.1 for some examples), the minimal selection is induced by its barycenter. In this case, the latter is referred to as the *Wasserstein gradient* (see Definition 20 below) $\nabla_\mu\phi(\mu) : \mathbb{R}^d \rightarrow \mathbb{R}^d$ of the functional $\phi(\cdot)$ at μ .

The goal of this paper is to prove the Pontryagin-type optimality conditions for (\mathcal{P}) that we introduce in the following main result. In the sequel, we will denote by $B_{2d}(0, R)$ the ball of radius R centered at 0 in \mathbb{R}^{2d} , by $\pi^1, \pi^2 : \mathbb{R}^{2d} \rightarrow \mathbb{R}^d$ the projection operators on the first and second components and by K a generic compact subset of \mathbb{R}^d .

Theorem 1 (Pontryagin Maximum Principle for (\mathcal{P})). *Let $(u^*(\cdot), \mu^*(\cdot)) \in \mathcal{U} \times \text{Lip}([0, T], \mathcal{P}_c(\mathbb{R}^d))$ be an optimal pair control-trajectory for (\mathcal{P}) and assume that the following hypotheses **(H)** hold :*

(H)

(U) : *The set of admissible controls is $\mathcal{U} = L^1([0, T], U)$ where $U \subset C^1(\mathbb{R}^d, \mathbb{R}^d)$ is a non-empty and closed subset of $\left\{ v \in C^1(\mathbb{R}^d, \mathbb{R}^d) \text{ s.t. } \|v(\cdot)\|_{C^0(\mathbb{R}^d)} + \text{Lip}(v(\cdot), \mathbb{R}^d) \leq L_U \right\}$ for a given constant $L_U > 0$.*

(L) : *The running cost $L : (\mu, \omega) \in \mathcal{P}_c(\mathbb{R}^d) \times U \mapsto L(\mu, \omega) \in \mathbb{R}$ is Lipschitz in (μ, ω) with respect to the product metric $W_2 \times C^0$ over $\mathcal{P}(K) \times U$ for any compact set $K \subset \mathbb{R}^d$. The functional $\mu \in \mathcal{P}(K) \mapsto L(\mu, \omega)$ is proper, regular in the sense of Definition 19 below, bounded for any $\omega \in U$ and $K \subset \mathbb{R}^d$ compact.*

(C) : *The terminal cost $\varphi : \mu \in \mathcal{P}_c(\mathbb{R}^d) \mapsto \varphi(\mu) \in \mathbb{R}$ is proper, regular in the sense of Definition 19 below, Lipschitz with respect to the W_2 -metric, bounded from below over $\mathcal{P}(K)$ for any compact set $K \subset \mathbb{R}^d$.*

(F) : The non-local velocity field $v : \mu \in \mathcal{P}_c(\mathbb{R}^d) \mapsto v[\mu](\cdot, \cdot) \in L^1([0, T], C^1(\mathbb{R}^d, \mathbb{R}^d) \cap L^\infty(\mathbb{R}^d, \mathbb{R}^d))$ satisfies

$$|v[\mu](t, x)| \leq M(1 + |x|), \quad |v[\mu](t, x) - v[\mu](t, y)| \leq L_1|x - y|,$$

and $\|v[\mu](t, \cdot) - v[\nu](t, \cdot)\|_{C^0(\mathbb{R}^d)} \leq L_2W_1(\mu, \nu)$

for \mathcal{L}^1 -almost every $t \in [0, T]$ and all $(x, y) \in \mathbb{R}^d \times \mathbb{R}^d$ where M, L_1 and L_2 are positive constants. For any compact set $K \subset \mathbb{R}^d$ and any $i \in \{1, \dots, d\}$, the components $\mu \in \mathcal{P}(K) \mapsto v^i[\mu](t, x)$ are regular in the sense of Definition 19 below.

(B) : The barycenter $x \mapsto \bar{\gamma}_\varphi^\circ(x)$ of the minimal selection $\partial^\circ \varphi(\mu)$ in the extended subdifferential of the terminal cost $\varphi(\cdot)$ at some measure $\mu \in \mathcal{P}_c(\mathbb{R}^d)$ is continuous.

The barycenter $x \mapsto \bar{\gamma}_L^\circ(x)$ of the minimal selection $\partial_\mu^\circ L(\mu, \omega)$ in the extended subdifferential of the running cost $L(\cdot, \omega)$ at some $\mu \in \mathcal{P}_c(\mathbb{R}^d)$ is locally bounded.

The barycenter $x \in \mathbb{R}^d \mapsto \bar{\gamma}_{(t,y)}^{i,\circ}(x)$ of the minimal selections $\partial_\mu^\circ v^i[\mu](t, y)$ in the extended subdifferentials of the components (v^i) of the non-local vector field $v[\mu](t, x)$ at some $\mu \in \mathcal{P}_c(\mathbb{R}^d)$ is locally bounded for all $(t, y) \in [0, T] \times \mathbb{R}^d$. The map $y \in \mathbb{R}^d \mapsto \bar{\gamma}_{(t,y)}^{i,\circ}(x)$ is continuous for all $(t, x) \in [0, T] \times \mathbb{R}^d$.

(D) : The maps $\mu \in \mathcal{P}_c(\mathbb{R}^d) \mapsto \varphi(\mu)$, $\mu \in \mathcal{P}_c(\mathbb{R}^d) \mapsto L(\mu, \omega)$ and $\mu \in \mathcal{P}_c(\mathbb{R}^d) \mapsto v[\mu](t, x)$ are differentiable along measure curves generated by Lipschitz-in-time, continuous and bounded perturbations of the identity for $\mathcal{L}^1 \times \mu$ -almost every $(t, x) \in [0, T] \times \mathbb{R}^d$ and any $\omega \in U$, i.e.

$$\begin{aligned} \frac{d^+}{d\epsilon} [\phi(\mathcal{G}(\epsilon, \cdot) \# \mu)] &= \frac{d^-}{d\epsilon} [\phi(\mathcal{G}(\epsilon, \cdot) \# \mu)], \quad \frac{d^+}{d\epsilon} [L(\mathcal{G}(\epsilon, \cdot) \# \mu, \omega)] = \frac{d^-}{d\epsilon} [L(\mathcal{G}(\epsilon, \cdot) \# \mu, \omega)] \\ \frac{d^+}{d\epsilon} [v[\mathcal{G}(\epsilon, \cdot) \# \mu](t, x)] &= \frac{d^-}{d\epsilon} [v[\mathcal{G}(\epsilon, \cdot) \# \mu](t, x)] \end{aligned}$$

whenever $(\mathcal{G}(\epsilon, \cdot))_{(-\bar{\epsilon}, \bar{\epsilon})}$ is a Lipschitz family of continuous and bounded maps, differentiable at $\epsilon = 0$ and such that $\mathcal{G}(0, \cdot) = I_d$.

Then, there exist a constant $R > 0$ depending on $\mu^0, T, U, v[\cdot](\cdot, \cdot), \varphi(\cdot), L(\cdot, \cdot)$ and a curve $\nu^*(\cdot) \in \text{Lip}([0, T], \mathcal{P}(\overline{B_{2d}(0, R)}))$ Lipschitzian with respect to the W_1 -metric satisfying the following conditions :

(i) It solves the forward-backward system of continuity equations

$$\begin{cases} \partial_t \nu^*(t) + \nabla_{(x,r)} \cdot (\mathbb{J}_{2d} \tilde{\nabla}_\nu \mathbb{H}_c(t, \nu^*(t), u^*(t)) \nu^*(t)) = 0 & \text{in } [0, T] \times \mathbb{R}^{2d}, \\ \pi_{\#}^1 \nu^*(0) = \mu^0, \\ \pi_{\#}^2 \nu^*(T) = (-\bar{\gamma}_\varphi^\circ) \# \mu^*(T), \end{cases} \quad (2)$$

where $\bar{\gamma}_\varphi^\circ(\cdot)$ is the barycenter of the minimal selection $\partial^\circ \varphi(\mu^*(T))$ of the final cost $\varphi(\cdot)$ at $\mu^*(T)$ and $\mathbb{J}_{2d} = \begin{pmatrix} 0 & I_d \\ -I_d & 0 \end{pmatrix}$ is the symplectic matrix in \mathbb{R}^{2d} .

The compactified Hamiltonian of the system $\mathbb{H}_c(\cdot, \cdot, \cdot)$ is defined by

$$\mathbb{H}_c : (t, \nu, \omega) \in [0, T] \times \mathcal{P}_c(\mathbb{R}^{2d}) \times U \mapsto \begin{cases} \mathbb{H}(t, \nu, \omega) & \text{if } \nu \in \mathcal{P}(\overline{B_{2d}(0, R)}), \\ +\infty & \text{otherwise,} \end{cases} \quad (3)$$

where

$$\mathbb{H} : (t, \nu, \omega) \in [0, T] \times \mathcal{P}_c(\mathbb{R}^{2d}) \times U \mapsto \int_{\mathbb{R}^{2d}} \langle r, v[\pi_{\#}^1 \nu](t, x) + \omega(x) \rangle d\nu(x, r) - L(\pi_{\#}^1 \nu, \omega) \quad (4)$$

is the infinite dimensional Hamiltonian of the system.

The vector field $\tilde{\nabla}_\nu \mathbb{H}_c(t, \nu^*(t), u^*(t))(\cdot, \cdot)$ is defined by

$$\tilde{\nabla}_\nu \mathbb{H}_c(t, \nu^*(t), u^*(t)) : (x, r) \in \text{supp}(\nu^*(t)) \mapsto \begin{pmatrix} \mathbb{D}_x u^*(t, x)^\top r + \mathbb{D}_x v[\pi_{\#}^1 \nu^*(t)](t, x)^\top r + \mathbb{I}_v^\circ[\nu^*(t)](t, x) - \bar{\gamma}_L^\circ(t, x) \\ v[\pi_{\#}^1 \nu^*(t)](t, x) + u^*(t, x) \end{pmatrix}$$

where $t \in [0, T] \mapsto \bar{\gamma}_L^\circ(t, \cdot)$ is a measurable selection of the barycenters of $\partial_\mu^\circ L(\mu^*(t), u^*(t))$. The map $\mathbb{I}_v^\circ[\nu^*(t)](\cdot, \cdot)$ is defined by

$$\mathbb{I}_v^\circ[\nu^*(t)] : (t, x) \in [0, T] \times \pi^1(\overline{B(0, R)}) \mapsto \int_{\mathbb{R}^{2d}} \left(\mathbb{I}_{(t, y)}^\circ(x) \right)^\top p \, d\nu^*(t)(y, p)$$

where for $\mathcal{L}^1 \times \pi_{\#}^1 \nu^*(\cdot)$ -almost every $(t, y) \in [0, T] \times \pi^1(\overline{B(0, R)})$ we define $\mathbb{I}_{(t, y)}^\circ : x \in \text{supp}(\mu^*(t)) \mapsto (\bar{\gamma}_{(t, y)}^{i, \circ}(x))_{1 \leq i \leq d}$ as the matrix-valued map made of the barycenters of the minimal selections $\partial_\mu^\circ v^i[\mu^*(t)](t, y)$ in the extended subdifferentials of the components (v^i) of the non-local velocity field.

(ii) It satisfies the Pontryagin maximization condition

$$\mathbb{H}_c(t, \nu^*(t), u^*(t)) = \max_{\omega \in U} [\mathbb{H}_c(t, \nu^*(t), \omega)] \quad \text{for } \mathcal{L}^1\text{-almost every } t \in [0, T]. \quad (5)$$

The general hypotheses **(H)** can sometimes be hard to verify. Nevertheless, they are implied by simpler hypotheses that are easier to check. Similarly, the dynamics (2) has some simpler expressions in several interesting cases. We discuss such examples in Section 1.1.

Remark 1. Observe that in our formulation of the PMP, the vector field $\tilde{\nabla}_\nu \mathbb{H}_c(t, \nu^*(t), u^*(t))$ is not the Wasserstein gradient of the compactified Hamiltonian $\mathbb{H}_c(\nu^*(t), u^*(t))$, since in general the barycenter of a minimal selection is not in the classical subdifferential. However, in any context where the minimal selections are induced by plans, which will automatically be their barycenters, or when they are strong subdifferentials, it can be shown by standard methods that $\tilde{\nabla}_\nu \mathbb{H}_c(t, \nu^*(t), u^*(t))$ is in fact the Wasserstein gradient of the compactified Hamiltonian at $(t, \nu^*(t), u^*(t))$ for \mathcal{L}^1 -almost every $t \in [0, T]$.

The structure of the article is the following : in Section 1.1 we list some relevant examples of classical functionals satisfying assumptions **(H)** and recall their Wasserstein subdifferential. In Section 2 we recall useful results of analysis in Wasserstein spaces, PDEs with non-local velocities and subdifferential calculus in $(\mathcal{P}_2(\mathbb{R}^d), W_2)$. We also prove in Theorem 5 an existence and characterization result for directional derivatives along measure curves for non-local flows. In Section 3 we prove the Pontryagin Maximum Principle in the Wasserstein Space : we first introduce in Section 3.1 the main steps of our proof on a simpler instance (\mathcal{P}_1) of problem (\mathcal{P}) - and in particular the concept of **needle like variation** -, and then prove our main result in Section 3.2.

1.1 Corollaries of the Pontryagin Maximum Principle

The aim of the general result stated in Theorem 1 is to provide first-order necessary optimality conditions that are adapted to a wide range of functionals. We give in the following Propositions some examples of minimal selections as well as common functionals that are encompassed in hypotheses **(H)**.

Proposition 2 (Subdifferential of a smooth integral functional). *Let $V \in C^1(\mathbb{R}^d, \mathbb{R})$ and $K \subset \mathbb{R}^d$ be a compact set and define $\mathcal{V} : \mu \in \mathcal{P}(K) \mapsto \int_{\mathbb{R}^d} V(x) d\mu(x)$. Then the functional $\mathcal{V}(\cdot)$ is regular at any $\mu \in \mathcal{P}(K)$ in the sense of Definition 19 below, Lipschitz in the W_1 -metric. Moreover, the minimal selection $\partial^\circ \mathcal{V}(\mu)$ in its extended subdifferential at μ is a classical strong subdifferential induced by a map and given explicitly by $\partial^\circ \mathcal{V}(\mu) = (I_d \times \nabla V)_{\#} \mu$.*

Proof. See e.g. [5, Proposition 10.4.2]. □

Remark 3. Taking any power $\alpha > 0$ of $\mathcal{V}(\cdot)$ yields the same results provided that the functional $x \mapsto x^\alpha$ is differentiable at $\mathcal{V}(\mu)$. In which case, the minimal selection in the extended subdifferential is induced

by the map

$$\nabla_\mu(\mathcal{V}^\alpha)(\mu) : x \in \text{supp}(\mu) \mapsto \alpha \mathcal{V}(\mu)^{\alpha-1} \nabla V(x). \quad (6)$$

Proposition 4 (Subdifferential of the variance functional). *Let $K \subset \mathbb{R}^d$ be a compact set and define the variance functional by*

$$\text{Var} : \mu \in \mathcal{P}(K) \mapsto \frac{1}{2} \int_{\mathbb{R}^d} |x - \bar{\mu}|^2 d\mu(x) = \frac{1}{2} \int_{\mathbb{R}^d} |x|^2 d\mu(x) - \frac{1}{2} |\bar{\mu}|^2$$

where $\bar{\mu} = \int_{\mathbb{R}^d} x d\mu(x)$ denotes the mean of the measure μ .

Then, the functional $\text{Var}(\cdot)$ is regular at any $\mu \in \mathcal{P}(K)$, Lipschitz in the W_1 -metric and the minimal selection $\partial^\circ \text{Var}(\mu)$ in its extended subdifferential is a classical strong subdifferential induced by the map $\nabla_\mu \text{Var}(\mu) : x \in \text{supp}(\mu) \mapsto x - \bar{\mu}$.

Proof. It is clear by definition of the variance functional that it is bounded from below over $\mathcal{P}(K)$. Moreover, an application of the *Kantorovich-Rubinstein* duality formula (9) yields the Lipschitzianity in the W_1 -metric. The regularity in the sense of Definition 19 can be verified by observing that the variance functional is convex along Wasserstein geodesics; this implies regularity (see [5, Lemma 10.3.8]).

We now show that $x \mapsto x - \bar{\mu}$ is in the classical strong subdifferential of the variance functional at $\mu \in \mathcal{P}(K)$. For any $\nu \in \mathcal{P}(K)$ and $\mu \in \Gamma(\mu, \nu)$, it holds that

$$\begin{aligned} \int_{\mathbb{R}^{2d}} \langle x_1 - \bar{\mu}, x_2 - x_1 \rangle d\mu(x_1, x_2) &= \int_{\mathbb{R}^{2d}} \langle x_1, x_2 \rangle d\mu(x_1, x_2) - \int_{\mathbb{R}^d} |x_1|^2 d\mu(x_1) + |\bar{\mu}|^2 - \langle \bar{\mu}, \bar{\nu} \rangle, \\ &\leq \frac{1}{2} \int_{\mathbb{R}^d} |x_2|^2 d\nu(x_2) - \frac{1}{2} \int_{\mathbb{R}^d} |x_1|^2 d\mu(x_1) + |\bar{\mu}|^2 - \langle \bar{\mu}, \bar{\nu} \rangle, \\ &\leq \text{Var}(\nu) - \text{Var}(\mu) + \frac{1}{2} |\bar{\mu} - \bar{\nu}|^2. \end{aligned}$$

Moreover, one can estimate the quantity $|\bar{\mu} - \bar{\nu}|^2$ as follows:

$$|\bar{\mu} - \bar{\nu}|^2 \leq \left(\int_{\mathbb{R}^{2d}} |x - y| d\gamma(x, y) \right)^2 = W_1^2(\mu, \nu) \leq W_2^2(\mu, \nu) \leq W_{2, \mu}^2(\mu, \nu) = o(W_{2, \mu}(\mu, \nu)).$$

where the first inequality holds for any $\gamma \in \Gamma(\mu, \nu)$ and the following equality is obtained by taking $\gamma \in \Gamma_o(\mu, \nu)$. The two remaining inequalities follow using the ordering of the Wasserstein metrics between compactly supported measures given in Proposition 15 and the definition of $W_{2, \mu}(\cdot, \cdot)$ given in Definition 18 below.

Therefore, we conclude that for any $\nu \in \mathcal{P}(K)$ and any $\mu \in \Gamma(\mu, \nu)$ it holds

$$\text{Var}(\nu) - \text{Var}(\mu) \geq \int_{\mathbb{R}^{2d}} \langle x_1 - \bar{\mu}, x_2 - x_1 \rangle d\mu(x_1, x_2) + o(W_{2, \mu}(\mu, \nu)).$$

which is equivalent to $x \in \text{supp}(\mu) \mapsto x - \bar{\mu}$ being a classical strong subdifferential at μ .

Now, take in particular $\nu \equiv \nu_s = (I_d + s\xi) \# \mu$ for some small $s > 0$ and $\xi \in C_c^\infty(\mathbb{R}^d)$ such that $\text{supp}(\nu_s) \subset \mathcal{P}(K)$. It then holds

$$+\infty > \lim_{s \downarrow 0} \left[\frac{\text{Var}((I_d + s\xi) \# \mu) - \text{Var}(\mu)}{s} \right] \geq \int_{\mathbb{R}^d} \langle x_1 - \bar{\mu}, \xi(x_1) \rangle d\mu(x_1).$$

Furthermore, one can check that it holds

$$\begin{aligned} \lim_{s \downarrow 0} \left[\frac{\text{Var}((I_d + s\xi) \# \mu) - \text{Var}(\mu)}{s} \right] &\leq \lim_{s \downarrow 0} \left[\frac{(\text{Var}((I_d + s\xi) \# \mu) - \text{Var}(\mu))^+}{W_2(\mu, (I_d + s\xi) \# \mu)} \right] \lim_{s \downarrow 0} \left[\frac{W_2(\mu, (I_d + s\xi) \# \mu)}{s} \right], \\ &\leq |\partial \text{Var}|(\mu) \|\xi\|_{L^2(\mu)}, \end{aligned}$$

so that, for any $\xi \in C_c^\infty(\mathbb{R}^d)$ with $\|\xi\|_{L^2(\mu)} \leq 1$, it holds

$$\int_{\mathbb{R}^d} \langle x_1 - \bar{\mu}, \xi(x_1) \rangle d\mu(x_1) \leq |\partial \text{Var}|(\mu).$$

By applying a density argument for test functions in the space $L^2(\mathbb{R}^d, \mathbb{R}^d; \mu)$ and using the dual characterization of the L^2 -norm of a functional, it finally holds that $\|I_d - \bar{\mu}\|_{L^2(\mu)} \leq |\partial \text{Var}|(\mu)$, which amounts to state by Theorem 3 that the strong subdifferential $x \in \text{supp}(\mu) \mapsto x - \bar{\mu}$ is the minimal selection in the classical subdifferential $\partial \text{Var}(\mu)$ of the variance functional at μ . \square

Remark 5 (Possible extensions). *Adding to the functionals we exhibited a measurable dependence in $t \in [0, T]$ would not alter our results. It would also be possible to consider integral functionals of the form*

$$\begin{cases} \mathcal{W}^k : \mu \in \mathcal{P}(K) \mapsto \int_{\mathbb{R}^d} W(x_1, \dots, x_k) d(\mu \times \dots \times \mu)(x_1, \dots, x_k) \\ \mathcal{V}_m : \mu \in \mathcal{P}(K) \mapsto \int_{\mathbb{R}^d} V(x, \int_{\mathbb{R}^d} m(y) d\mu(y)) d\mu(x) \end{cases}$$

for any $k \geq 1$, $W \in C^1(\mathbb{R}^{d \times k}, \mathbb{R})$, $V \in C^2(\mathbb{R}^d \times \mathbb{R}^n, \mathbb{R})$ and $m \in C^2(\mathbb{R}^d, \mathbb{R}^n)$ for some $n \geq 1$ without altering our results.

Proposition 6 (Subdifferential of a non-local vector field generated by a smooth interaction). *Let $K \subset \mathbb{R}^d$ be a compact set, $H(\cdot, \cdot) \in C^1(\mathbb{R}^{2d}, \mathbb{R}^d)$ be a function with sub-linear growth and consider the non-local velocity field $v\cdot : (\mu, x) \in \mathcal{P}_c(K) \times \mathbb{R}^d \mapsto \int_{\mathbb{R}^d} H(x, y) d\mu(y)$.*

*Then, $v[\cdot](\cdot, \cdot)$ satisfies **(F)**, **(B)** and **(D)** and the first order variations $x \in \text{supp}(\mu) \mapsto D_x v[\mu](x)$ and $x \in \text{supp}(\mu) \mapsto \int_{\mathbb{R}^d} \mathbb{I}_{(t,x)}^\circ(y) d\mu(y)$ can be computed explicitly as*

$$\begin{cases} D_x v[\mu](x) = \int_{\mathbb{R}^d} D_x H(x, y) d\mu(y), \\ \int_{\mathbb{R}^d} \mathbb{I}_x^\circ(y) d\mu(y) = \int_{\mathbb{R}^d} D_y H(x, y) d\mu(y). \end{cases}$$

where $\mathbb{I}_x^\circ(\cdot)$ is the matrix-valued map made of the barycenters $\bar{\gamma}_x^{i,\circ}(\cdot)$ of the minimal selections $\partial_\mu^\circ v^i[\mu](x)$ in the extended subdifferentials of the components (v^i) of the non-local velocity field at $x \in \mathbb{R}^d$.

Proof. The Lipschitz estimates and the regularity in the sense of Definition 19 can be derived using Kantorovich duality and the results of Proposition 2. For the first order variations, apply a classical differentiation under the integral sign result for the first one and Proposition 2 to the components $\mu \mapsto \int_{\mathbb{R}^d} H^i(x, y) d\mu(y)$ for any fixed $x \in \text{supp}(\mu)$ for the second one. \square

We summarize these results in the form of an overview of possible functions satisfying **(H)** in the following corollaries.

Corollary 7 (Example of terminal costs satisfying the hypotheses of Theorem 1). *If $\phi : \mathcal{P}(K) \mapsto \mathbb{R}$ is either a (suitable) power of a smooth integral functional or the variance functional, then it satisfies hypotheses **(C)**, **(B)** and **(D)**.*

Corollary 8 (Example of running costs satisfying the hypotheses of Theorem 1). *Let $l : (x, \omega) \in \mathbb{R}^d \times \mathbb{R}^d \times \mathbb{R}^d \mapsto l(t, x, \omega) \in \mathbb{R}$ be a C^1 function $K \subset \mathbb{R}^d$ be compact, and define the running cost $L : (\mu, \omega) \in \mathcal{P}(K) \times U \mapsto \mathbb{R}$ by*

$$L(\mu, \omega) = \int_{\mathbb{R}^d} l(x, \omega(x)) d\mu(x).$$

*Then, $L(\cdot, \cdot)$ satisfies hypotheses **(L)**, **(B)** and **(D)**. Moreover, the barycenter of the minimal selection in its extended subdifferential $\partial_\mu^\circ L(\mu, \omega)$ is determined at any $\mu \in \mathcal{P}(K)$ by*

$$\bar{\gamma}_L^\circ \equiv \nabla_\mu L(\mu, \omega) : x \in \text{supp}(\mu) \mapsto \nabla_x l(x, \omega(x)) + D_x \omega(x)^\top \nabla_u l(x, \omega(x)).$$

Proof. The proof only involves elementary Lipschitz-type estimates and the use of Proposition 2. \square

Notice again that it is possible to take any power $\alpha \geq 1$ of the previous cost and any power $\alpha > 0$ provided that the functional does not vanish along the optimal pair control-trajectory $(u^*(\cdot), \mu^*(\cdot)) \in \text{Lip}([0, T], \mathcal{P}_c(\mathbb{R}^d)) \times \mathcal{U}$.

The following result shows that functionals based on kernels are regular. They appear in several mean-field models for interaction, see e.g. [7, 8, 14, 21, 26, 29, 31].

Corollary 9 (Example of non-local vector fields satisfying the hypotheses of Theorem 1). *If $v[\cdot](\cdot, \cdot) : \mathcal{P}(K) \times [0, T] \times K \rightarrow \mathbb{R}^d$ is defined for any (μ, t, x) by*

$$v[\mu](t, x) = (H(t, \cdot) \star \mu(t))(x) + v_l(t, x),$$

for some sublinear interaction kernel $H \in L^\infty([0, T], C^1(\mathbb{R}^d, \mathbb{R}^d))$ and vector field $v_l(\cdot, \cdot)$ measurable in t as well as sublinear and Lipschitz in x , then it satisfies hypotheses **(F)**, **(B)** and **(C)**.

When the compactified Hamiltonian of the system $\omega \in U \mapsto \mathbb{H}_c(t, \nu^*(t), \omega)$ is differentiable at $u^*(t)$ for \mathcal{L}^1 -almost every $t \in [0, T]$, the maximization condition can be rewritten as a usual first-order condition.

Corollary 10 (Differentiation of the Hamiltonian). *Suppose that $u^*(t) \in \text{int}(U)$ for \mathcal{L}^1 -almost every $t \in [0, T]$ and that the compactified Hamiltonian $\omega \in U \mapsto \mathbb{H}_c(t, \nu^*(t), \omega)$ is Fréchet differentiable at $u^*(t)$ for \mathcal{L}^1 -almost every $t \in [0, T]$. Then $u^*(t)$ verifies:*

$$D_\omega \mathbb{H}_c(t, \nu^*(t), u^*(t)) \cdot v = 0 \quad (7)$$

for all $v \in U$ and for \mathcal{L}^1 -almost every $t \in [0, T]$.

2 Analysis in Wasserstein spaces

In this section, we recall several notions about analysis in the space of probability measures, optimal transport theory, Wasserstein spaces, continuity equations and subdifferential calculus in the space $(\mathcal{P}_2(\mathbb{R}^d), W_2)$. We prove also a differentiation result for non-local flows of diffeomorphisms with respect to their initial measure in Theorem 5.

2.1 The Optimal Transport problem and Wasserstein spaces

In this section, we introduce some classical notations and results of optimal transport and analysis in Wasserstein spaces.

We denote by $\mathcal{P}(\mathbb{R}^d)$ the space of Borel probability measures over \mathbb{R}^d , and by $\mathcal{P}_p(\mathbb{R}^d)$ for some $p \geq 1$ the subset of $\mathcal{P}(\mathbb{R}^d)$ of measures having finite p -th moment, i.e.

$$\mathcal{P}_p(\mathbb{R}^d) = \left\{ \mu \in \mathcal{P}(\mathbb{R}^d) \text{ s.t. } \int_{\mathbb{R}^d} |x|^p d\mu(x) < +\infty \right\}.$$

The *support* of a Borel probability measure $\mu \in \mathcal{P}(\mathbb{R}^d)$ is defined as the closed set $\text{supp}(\mu) = \{x \in \mathbb{R}^d \text{ s.t. } \mu(\mathcal{N}) > 0 \text{ for any neighbourhood } \mathcal{N} \text{ of } x\}$. We denote by $\mathcal{P}_c(\mathbb{R}^d)$ the subset of $\mathcal{P}(\mathbb{R}^d)$ of measures which supports are compact.

We say that a sequence $(\mu_n) \subset \mathcal{P}(\mathbb{R}^d)$ of Borel probability measures *converges narrowly* towards $\mu \in \mathcal{P}(\mathbb{R}^d)$, denoted by $\mu_n \rightarrow \mu$, provided that

$$\int_{\mathbb{R}^d} \phi(x) d\mu_n(x) \xrightarrow{n \rightarrow +\infty} \int_{\mathbb{R}^d} \phi(x) d\mu(x) \text{ for all } \phi \in C_b^0(\mathbb{R}^d) \quad (8)$$

where $C_b^0(\mathbb{R}^d)$ denotes the set of continuous and bounded functions from \mathbb{R}^d into \mathbb{R} .

We recall the definitions of *pushforward* of a Borel probability measure through a Borel map and *transport plan*.

Definition 11 (Pushforward of a measure through a Borel map). *Given a Borel probability measure $\mu \in \mathcal{P}(\mathbb{R}^d)$ and a Borel map $f : \mathbb{R}^d \rightarrow \mathbb{R}^d$, the pushforward $f_\# \mu$ of μ through f is defined by $f_\# \mu(B) = \mu(f^{-1}(B))$ for any Borel set $B \subset \mathbb{R}^d$.*

Definition 12 (Transport plan). *Given two probability measures μ and ν on \mathbb{R}^d , we say that $\gamma \in \mathcal{P}(\mathbb{R}^d \times \mathbb{R}^d)$ is a transport plan between μ and ν , denoted by $\gamma \in \Gamma(\mu, \nu)$, provided that $\gamma(A \times \mathbb{R}^d) = \mu(A)$ and $\gamma(\mathbb{R}^d \times B) = \nu(B)$ for any Borel subsets $A, B \subset \mathbb{R}^d$. Equivalently, it satisfies $\pi_{\#}^1 \gamma = \mu$ and $\pi_{\#}^2 \gamma = \nu$.*

Given a probability measure $\gamma \in \mathbb{R}^{2d}$, we also denote by $\Gamma(\gamma, \nu)$ the set of plans $\mu \in \mathcal{P}(\mathbb{R}^{3d})$ such that $\pi_{\#}^{1,2} \mu = \gamma$ and $\pi_{\#}^3 \mu = \nu$ where $\pi^{1,2} : (x, y, z) \in \mathbb{R}^{3d} \mapsto (x, y) \in \mathbb{R}^{2d}$.

We recall in the following Proposition three useful convergence results for sequences of probability measures and functions (see e.g. [5, Chapter 5]).

Proposition 13 (Convergence results). *Let $(\mu_n) \subset \mathcal{P}(\mathbb{R}^d)$ be a sequence narrowly converging to $\mu \in \mathcal{P}(\mathbb{R}^d)$, (f_n) be a sequence of μ -measurable functions pointwisely converging to f and $g \in C^0(\mathbb{R}^d)$.*

- (i) *Suppose that $x \mapsto |g(x)|$ is uniformly integrable with respect to the family $\{\mu_n\}_{n=1}^\infty$, i.e. $\lim_{k \rightarrow +\infty} \int_{\{|g(x)| \geq k\}} |g(x)| d\mu_n(x) = 0$ for all $n \geq 1$. Then, the sequence $(\int_{\mathbb{R}^d} g(x) d\mu_n(x)) \subset \mathbb{R}$ converges to $\int_{\mathbb{R}^d} g(x) d\mu(x)$ as $n \rightarrow +\infty$.*

(ii) The sequence $(g_{\#}\mu_n) \subset \mathcal{P}(\mathbb{R}^d)$ narrowly converges to $g_{\#}\mu$ as $n \rightarrow +\infty$.

(iii) (Vitali convergence theorem) Suppose that the family $x \mapsto |f_n(x)|$ is uniformly integrable with respect to the measure μ , i.e. $\lim_{k \rightarrow +\infty} \int_{\{|f_n(x)| \geq k\}} |f_n(x)| d\mu(x) = 0$ for all $n \geq 1$ and also assume that $|f(x)| < +\infty$ for μ -almost every $x \in \mathbb{R}^d$. Then (f_n) converges uniformly to f in $L^1(\mathbb{R}^d; \mu)$ as $n \rightarrow +\infty$.

In the 40's, Kantorovich introduced the *optimal mass transportation problem* in its modern mathematical formulation : given two probability measures $\mu, \nu \in \mathcal{P}(\mathbb{R}^d)$ and a cost function $c : \mathbb{R}^d \times \mathbb{R}^d \rightarrow \mathbb{R}$, find a *transport plan* $\gamma \in \Gamma(\mu, \nu)$ such that

$$\int_{\mathbb{R}^{2d}} c(x, y) d\gamma(x, y) = \min \left\{ \int_{\mathbb{R}^{2d}} c(x, y) d\gamma'(x, y) \text{ s.t. } \gamma' \in \Gamma(\mu, \nu) \right\}.$$

This problem has been extensively studied in very broad contexts (see e.g. [5, 30]) with high levels of generality on the underlying spaces and cost functions. In the particular case where $c(x, y) = |x - y|^p$ for some real number $p \geq 1$, the optimal transport problem can be used to define a distance over the subspace $\mathcal{P}_p(\mathbb{R}^d)$ of $\mathcal{P}(\mathbb{R}^d)$.

Definition 14 (Wasserstein distance and Wasserstein spaces). *Given two probability measures $\mu, \nu \in \mathcal{P}_p(\mathbb{R}^d)$, the p -Wasserstein distance W_p between μ and ν is defined by*

$$W_p(\mu, \nu) = \min \left\{ \left(\int_{\mathbb{R}^{2d}} |x - y|^p d\gamma(x, y) \right)^{1/p} \text{ s.t. } \gamma \in \Gamma(\mu, \nu) \right\}.$$

The set of plans $\gamma \in \Gamma(\mu, \nu)$ achieving this optimal value is denoted¹ by $\Gamma_o(\mu, \nu)$ and referred to as the set of optimal transport plans between μ and ν . The space $(\mathcal{P}_p(\mathbb{R}^d), W_p)$ of probability measures with finite p -th moment endowed with the p -th Wasserstein metric is called the Wasserstein space of order p .

We recall some of the interesting properties of these spaces in the following Proposition (see e.g. [5, Chapter 7] or [30, Chapter 6]).

Proposition 15 (Properties of the Wasserstein distance). *The topology induced in $\mathcal{P}_p(\mathbb{R}^d)$ by the Wasserstein metric W_p metrizes the weak topology of probability measures induced by the narrow convergence (8), i.e.*

$$W_p(\mu_n, \mu) \xrightarrow{n \rightarrow +\infty} 0 \iff \mu_n \rightharpoonup \mu \text{ and } \int_{\mathbb{R}^d} |x|^p d\mu_n(x) \rightarrow \int_{\mathbb{R}^d} |x|^p d\mu(x)$$

For compactly supported measures $\mu, \nu \in \mathcal{P}_c(\mathbb{R}^d)$, the Wasserstein distances are ordered, i.e. $p_1 \leq p_2 \implies W_{p_1}(\mu, \nu) \leq W_{p_2}(\mu, \nu)$.

When $\mu, \nu \in \mathcal{P}_c(\mathbb{R}^d)$ and $p = 1$, the following Kantorovich-Rubinstein duality formula holds :

$$W_1(\mu, \nu) = \sup \left\{ \int_{\mathbb{R}^d} \phi(x) d(\mu - \nu)(x) \text{ s.t. } \text{Lip}(\phi, \mathbb{R}^d) \leq 1 \right\}. \quad (9)$$

In what follows, we shall mainly restrict our considerations to the Wasserstein spaces of order 1 and 2 built over $\mathcal{P}_c(\mathbb{R}^d)$. We end this introductory paragraphs by recalling the concepts of *disintegration* and *barycenter* in the context of optimal transport.

Definition 16 (Disintegration and barycenter). *Let $\mu, \nu \in \mathcal{P}_p(\mathbb{R}^d)$ and $\gamma \in \Gamma(\mu, \nu)$ be a transport plan between μ and ν . We define the disintegration $\{\gamma_x\}_{x \in \mathbb{R}^d} \subset \mathcal{P}_p(\mathbb{R}^d)$ on its first marginal μ , usually denoted by $\gamma = \int \gamma_x d\mu(x)$, as the μ -almost uniquely determined Borel family of probability measures such that*

$$\int_{\mathbb{R}^{2d}} \phi(x, y) d\gamma(x, y) = \int_{\mathbb{R}^d} \int_{\mathbb{R}^d} \phi(x, y) d\gamma_x(y) d\mu(x) \text{ for any } \phi \in C_0^b(\mathbb{R}^{2d}).$$

The barycenter $\bar{\gamma} \in L^p(\mathbb{R}^d, \mathbb{R}^d; \mu)$ of the plan γ is then defined by

$$\bar{\gamma} : x \in \text{supp}(\mu) \mapsto \int_{\mathbb{R}^d} y d\gamma_x(y).$$

¹We omit the dependence on p for clarity and conciseness.

2.2 The continuity equation on \mathbb{R}^d with non-local velocities

In this section, we introduce the continuity equations with non-local velocities in $(\mathcal{P}_c(\mathbb{R}^d), W_1)$. These equations write

$$\partial_t \mu(t) + \nabla \cdot (v[\mu(t)](t, \cdot) \mu(t)) = 0. \quad (10)$$

where $t \mapsto \mu(t)$ is a narrowly continuous family of probability measures on \mathbb{R}^d and $(t, x) \mapsto v[\mu](t, x)$ is a Borel family of vector fields for any $\mu \in \mathcal{P}_c(\mathbb{R}^d)$ satisfying the condition

$$\int_0^T \int_{\mathbb{R}^d} |v[\mu(t)](t, x)| d\mu(t)(x) dt < +\infty. \quad (11)$$

Equation (10) has to be understood in the sense of distributions, i.e.

$$\int_0^T \int_{\mathbb{R}^d} (\partial_t \phi(t, x) + \langle \nabla_x \phi(t, x), v[\mu(t)](t, x) \rangle) d\mu(t)(x) dt = 0 \quad \text{for all } \phi \in C_c^\infty([0, T] \times \mathbb{R}^d), \quad (12)$$

or alternatively as

$$\frac{d}{dt} \int_{\mathbb{R}^d} \phi(x) d\mu(t)(x) = \int_{\mathbb{R}^d} \langle \nabla \phi(x), v[\mu(t)](t, x) \rangle d\mu(t)(x) \quad \text{for all } \phi \in C_c^\infty(\mathbb{R}^d), \quad (13)$$

for \mathcal{L}^1 -almost every $t \in [0, T]$.

As already mentioned in the Introduction, these equations are interesting for a large number of applications. It is important to notice that $v[\mu]$ depends on the whole measure μ and not only on its values at some points as it is usually the case for hyperbolic PDEs.

We now recall a Theorem which was first derived in [4] providing existence, uniqueness and representation formula for solutions of (10). We state here a version explored in [27, 28] that is more suited to our control-theoretic framework.

Theorem 2 (Existence, uniqueness and representation of solutions for (10)). *Consider a non-local velocity field $v[\cdot](\cdot, \cdot)$ defined as*

$$v : \mu \in \mathcal{P}_c(\mathbb{R}^d) \mapsto v[\mu](\cdot, \cdot) \in L^\infty(\mathbb{R}, C^1(\mathbb{R}^d, \mathbb{R}^d) \cap L^\infty(\mathbb{R}^d)), \quad (14)$$

and satisfying the following assumptions

(H')

◇ There exists positive constants L_1 and M such that

$$|v[\mu](t, x) - v[\mu](t, y)| \leq L_1 |x - y| \quad \text{and} \quad |v[\mu](t, x)| \leq M(1 + |x|)$$

for every $\mu \in \mathcal{P}_c(\mathbb{R}^d)$, $t \in \mathbb{R}$ and $(x, y) \in \mathbb{R}^d \times \mathbb{R}^d$;

◇ There exists a positive constant L_2 such that

$$\|v[\mu](t, \cdot) - v[\nu](t, \cdot)\|_{C^0(\mathbb{R}^d)} \leq L_2 W_1(\mu, \nu)$$

for every $\mu, \nu \in \mathcal{P}_c(\mathbb{R}^d)$ and $t \in \mathbb{R}$;

Then for every initial datum $\mu^0 \in \mathcal{P}_c(\mathbb{R}^d)$, the Cauchy problem

$$\begin{cases} \partial_t \mu(t) + \nabla \cdot (v[\mu(t)](t, \cdot) \mu(t)) = 0 \\ \mu(0) = \mu^0, \end{cases} \quad (15)$$

admits a unique solution $\mu(\cdot)$ in $C^0(\mathbb{R}, \mathcal{P}_c(\mathbb{R}^d))$. This solution is locally Lipschitz in t with respect to the W_1 -metric. Besides, if μ^0 is absolutely continuous with respect to the Lebesgue measure, then $\mu(t)$ is also absolutely continuous for all times $t \geq 0$.

Furthermore for every $T > 0$ and every $\mu^0, \nu^0 \in \mathcal{P}_c(\mathbb{R}^d)$, there exists $R_T > 0$ depending on $\text{supp}(\mu^0)$ and $C_T > 0$ such that

$$\text{supp}(\mu(t)) \subset \overline{B(0, R_T)} \quad \text{and} \quad W_1(\mu(t), \nu(t)) \leq C_T W_1(\mu^0, \nu^0),$$

for all times $t \in [0, T]$ and any solutions $\mu(\cdot), \nu(\cdot)$ of (15).

Moreover, let $(\Phi_{(0,t)}^v[\mu^0](\cdot))_{t \geq 0}$ be the family of flows of diffeomorphisms generated by the non-local vector field $v[\mu(t)](t, \cdot)$, defined as the unique solution of

$$\partial_t \Phi_{(0,t)}^v[\mu^0](x) = v[\mu(t)]\left(t, \Phi_{(0,t)}^v[\mu^0](x)\right), \quad \left(\Phi_{(0,t)}^v[\mu^0](x)\right)_{|t=0} = x \quad \text{for all } x \text{ in } \mathbb{R}^d. \quad (16)$$

Then, the unique solution of the Cauchy problem (15) is expressed at time t as $\mu(t) = \Phi_{(0,t)}^v[\mu^0](\cdot) \# \mu^0$.

We recall below a standard result of the theory of finite dimensional ODEs, which links the differential of the flow of diffeomorphisms of an ODE at time t to the solution of a corresponding linearised Cauchy problem (see e.g. [10]).

Proposition 17 (Differential of a flow). *Let $(t, x) \mapsto v(t, x)$ be measurable in t as well as sublinear and C^1 in x . Define the family of C^1 -flows $(\Phi_t^v(\cdot))_{t \geq 0}$ associated to $v(\cdot, \cdot)$ by (16) in the case where $v(\cdot, \cdot)$ is independent from $\mu(\cdot)$.*

Then, it holds that the differential $D_x \Phi_{(s,t)}^v(x) \cdot h$ of the flow between times s and t , evaluated at x and applied to some vector $h \in \mathbb{R}^d$ is the unique solution $w(\cdot, x)$ of the linearised Cauchy problem

$$\partial_t w(t, x) = D_x v(t, \Phi_{(s,t)}^v(x)) \cdot w(t, x), \quad w(s, x) = h.$$

This characterization is essential for proving the Pontryagin Maximum Principle in the usual finite dimensional setting using the needle-like variations approach. We shall prove in Theorem 5 a generalization of this result in the non-local case where the initial measure is perturbed by a Lipschitz family of continuous and bounded maps. Such a result is crucial to study the first order perturbation induced by a needle-like variation on a measure curve in the non-local setting.

2.3 Subdifferential calculus in $(\mathcal{P}_2(\mathbb{R}^d), W_2)$

In this section, we recall some elements of subdifferential calculus in the Wasserstein space $(\mathcal{P}_2(\mathbb{R}^d), W_2)$. For a thorough introduction, see [5, Chapters 9-11] where the full theory is developed and applied to the study of gradient flows.

Throughout this section, we denote by $\phi : \mathcal{P}_2(\mathbb{R}^d) \rightarrow (-\infty, +\infty]$ a proper, lower-semicontinuous functional. We denote the effective domain $D(\phi)$ of $\phi(\cdot)$ as the set of points where it is finite, i.e.

$$D(\phi) = \{\mu \in \mathcal{P}_2(\mathbb{R}^d) \text{ s.t. } \phi(\mu) < +\infty\}.$$

We further assume that for $\tau_* > 0$ small enough, the *Moreau-Yosida* relaxation of $\phi(\cdot)$ defined by

$$\Phi_M(\mu, \tau; \cdot) : \nu \mapsto \frac{1}{2\tau} W_2^2(\mu, \nu) + \phi(\nu) \quad (17)$$

attains a minimum at some $\mu_\tau \in D(\phi)$ for any $\tau \in (0, \tau_*)$. This technical assumption is satisfied whenever $\phi(\cdot)$ is bounded from below and at least lower-semicontinuous and is crucial for proving the main results of the theory developed in [5, Chapter 10].

We start by introducing the concept of *extended subdifferentials* for a functional defined over the Wasserstein space $(\mathcal{P}_2(\mathbb{R}^d), W_2)$.

Definition 18 (Extended subdifferential). *Let $\mu^1 \in D(\phi)$. We say that a transport plan $\gamma \in \mathcal{P}_2(\mathbb{R}^d \times \mathbb{R}^d)$ belongs to the extended (Fréchet) subdifferential $\partial\phi(\mu^1)$ of ϕ at μ^1 provided that*

- (i) $\pi_{\#}^1 \gamma = \mu^1$,
- (ii) $\forall \mu^3 \in \mathcal{P}_2(\mathbb{R}^d)$, $\phi(\mu^3) - \phi(\mu^1) \geq \inf_{\mu \in \Gamma_o^{1,3}(\gamma, \mu^3)} \left[\int_{\mathbb{R}^{3d}} \langle x_2, x_3 - x_1 \rangle d\mu \right] + o(W_2(\mu^1, \mu^3))$.

where $\Gamma_o^{1,3}(\gamma, \mu^3) = \{\mu \in \Gamma(\gamma, \mu^3) \text{ s.t. } \pi_{\#}^{1,3} \mu \in \Gamma_o(\mu^1, \mu^3)\}$. Moreover, we say that an extended subdifferential γ is induced by a plan if there exists $\xi \in L^2(\mathbb{R}^d, \mathbb{R}^d; \mu^1)$ such that $\gamma = (I_d \times \xi) \# \mu^1$. In which case, $\xi(\cdot)$ belongs to the classical subdifferential $\partial\phi(\mu)$ of $\phi(\cdot)$ at μ .

We say that a transport plan $\gamma \in \mathcal{P}_2(\mathbb{R}^d \times \mathbb{R}^d)$ belongs to the strong extended subdifferential $\partial_S \phi(\mu^1)$ of $\phi(\cdot)$ at μ^1 if the following stronger condition holds

$$\forall \mu^3 \in \mathcal{P}_2(\mathbb{R}^d), \forall \mu \in \Gamma(\gamma, \mu^3), \phi(\mu^3) - \phi(\mu^1) \geq \int_{\mathbb{R}^{3d}} \langle x_2, x_3 - x_1 \rangle d\mu + o(W_{2,\mu}(\mu^1, \mu^3)). \quad (18)$$

where for $\mu \in \mathcal{P}(\mathbb{R}^{3d})$ the quantity $W_{2,\mu}(\mu^1, \mu^3)$ is defined by

$$W_{2,\mu}(\mu^1, \mu^3) = \left(\int_{\mathbb{R}^{2d}} |x_1 - x_3|^2 d\mu(x_1, x_2, x_3) \right)^{1/2}.$$

We introduce in the next definition two technical notions that will prove useful in order to characterize the fact that an extended subdifferential is empty or not.

Definition 19 (Regular functionals over $(\mathcal{P}_2(\mathbb{R}^d), W_2)$ and metric slope). *A proper and lower semicontinuous functional $\phi(\cdot)$ is said to be regular provided that whenever $(\mu_n) \subset \mathcal{P}_2(\mathbb{R}^d)$ and $(\gamma_n) \subset \mathcal{P}_2(\mathbb{R}^{2d})$ are taken such that*

$$\mu_n \xrightarrow{W_2} \mu \text{ in } \mathcal{P}_2(\mathbb{R}^d), \quad \phi(\mu_n) \longrightarrow \tilde{\phi} \text{ in } \mathbb{R}, \quad \gamma_n \in \partial_S \phi(\mu_n) \quad \forall n \geq 1, \quad \gamma_n \xrightarrow{W_2} \gamma \text{ in } \mathcal{P}_2(\mathbb{R}^{2d}),$$

it implies that $\gamma \in \partial \phi(\mu)$ and $\tilde{\phi} = \phi(\mu)$.

Furthermore, we define the metric slope $|\partial \phi|(\mu)$ of the functional $\phi(\cdot)$ at $\mu \in D(\phi)$ as

$$|\partial \phi|(\mu) = \limsup_{\nu \rightarrow \mu} \left[\frac{(\phi(\mu) - \phi(\nu))^+}{W_2(\mu, \nu)} \right].$$

where $(\bullet)^+$ denotes the positive part.

We presented several examples of regular functionals in Section 1.1. We are now ready to state a general condition for the extended subdifferential of a lower-semicontinuous, proper and regular functional to be non-empty. The proof can be found in [5, Theorem 10.3.10].

Theorem 3 (Link between extended subdifferentials and metric slopes). *Let $\phi(\cdot)$ be a proper, lower-semicontinuous, bounded from below and regular functional over $\mathcal{P}_2(\mathbb{R}^d)$. Then, the extended subdifferential $\partial \phi(\mu)$ of $\phi(\cdot)$ at some $\mu \in D(\phi)$ is non-empty if and only if its metric slope $|\partial \phi|(\mu)$ at μ is finite.*

In which case, there exists a unique minimal selection in $\partial \phi(\mu)$, denoted by $\partial^\circ \phi(\mu)$, satisfying

$$\left(\int_{\mathbb{R}^{2d}} |r|^2 d(\partial^\circ \phi(\mu))(x, r) \right)^{1/2} = \min \left\{ \left(\int_{\mathbb{R}^{2d}} |r|^2 d\gamma(x, r) \right)^{1/2} \text{ s.t. } \gamma \in \partial \phi(\mu) \right\} = |\partial \phi|(\mu).$$

This minimal selection can be explicitly characterized as follows : let μ_τ be the minimizer of the Moreau-Yosida functional (17) for some $\tau \in (0, \tau_*)$. Then there exists a family of strong subdifferentials $(\gamma_\tau) \subset (\partial_S \phi(\mu_\tau))$ which converges towards $\partial^\circ \phi(\mu)$ in the W_2 -metric along any vanishing sequence $\tau_n \downarrow 0$.

Definition 20 (Wasserstein gradient). *Whenever the minimal selection $\partial^\circ \phi(\mu)$ is induced by a map, it is called the Wasserstein gradient of $\phi(\cdot)$. It is denoted by $\nabla_\mu \phi(\mu) \in L^2(\mathbb{R}^d, \mathbb{R}^d; \mu)$ and it coincides with the barycenter of the minimal selection.*

The main interest of subdifferential calculus in the space $(\mathcal{P}_2(\mathbb{R}^d), W_2)$ is to compute derivatives of functionals along measure curves. However, the general chain rule described in [5, Proposition 10.3.18] only applies to the case of a curve $\epsilon \mapsto \mu(\epsilon) = \mathcal{G}(\epsilon, \cdot) \# \mu$ generated by smooth functions $\mathcal{G}(\epsilon, \cdot)$ when one restricts himself to strong subdifferentials. Yet, there is no reason in general for the strong subdifferential of a functional to be non-empty. In Proposition 21, we condense some well known results of [5, Chapter 10] in order to provide a chain rule that allows to compute derivatives along smooth vector fields using the minimal selection $\partial^\circ \phi(\mu)$. For simplicity, we state this result in the framework of the Wasserstein space $\mathcal{P}_c(\mathbb{R}^d)$.

Proposition 21 (Minimal selection and chain rule along smooth vector fields). *Let $\mu \in \mathcal{P}_c(\mathbb{R}^d)$ and $K = \cup_{x \in \text{supp}(\mu)} \overline{B(x, 1)}$. Let $\phi : \mathcal{P}(K) \rightarrow (-\infty, +\infty]$ be a functional satisfying hypotheses **(C)** and **(D)** of Theorem 1. Define $\mathcal{G} \in \text{Lip}((-\bar{\epsilon}, \bar{\epsilon}), C^0(\mathbb{R}^d, \mathbb{R}^d))$ a family of continuous functions with $\mathcal{G}(0, \cdot) = I_d$, $\text{supp}(\mathcal{G}(\epsilon, \cdot) \# \mu) \subset K$ for all $\epsilon \in (-\bar{\epsilon}, \bar{\epsilon})$ and $\mathcal{F} : x \mapsto \frac{d}{d\epsilon} [\mathcal{G}(\epsilon, x)]_{\epsilon=0}$ being C^0 as well.*

Then it holds that

$$\frac{d}{d\epsilon} [\phi(\mathcal{G}(\epsilon, \cdot) \# \mu)]_{\epsilon=0} = \int_{\mathbb{R}^{2d}} \langle \bar{\gamma}^\circ(x), \mathcal{F}(x) \rangle d\mu(x),$$

where $\bar{\gamma}^\circ \in L^2(\mathbb{R}^d, \mathbb{R}^d; \mu)$ is the barycenter of $\partial^\circ \phi(\mu)$.

Proof. First remark that it holds for any $\nu \in \mathcal{P}(K)$

$$(\phi(\mu) - \phi(\nu))^+ \leq \text{Lip}(\phi, \mathcal{P}(K)) W_2(\mu, \nu)$$

where $\text{Lip}(\phi, \mathcal{P}(K))$ is the Lipschitz constant of $\phi(\cdot)$ on $\mathcal{P}(K)$. Hence, $|\partial\phi|(\mu)$ is uniformly bounded by $\text{Lip}(\phi, \mathcal{P}(K))$. Moreover, the assumption that $\phi(\cdot)$ is bounded from below and Lipschitz on sets of uniformly compactly supported measures implies that for $\tau_* > 0$ small enough, the Moreau-Yosida functional $\Phi_M(\mu, \tau; \cdot)$ defined in (17) attains a minimum point $\mu_\tau \in D(\phi) \subset \mathcal{P}(K)$ for any $\tau \in (0, \tau_*)$. Thus, by Theorem 3, $\partial\phi(\mu)$ is non-empty and contains at least the minimal selection $\partial^\circ \phi(\mu)$ at any $\mu \in \mathcal{P}(K)$.

Consider a sequence $(\tau_n) \subset (0, \tau_*)$ converging to 0 and the corresponding sequence of strong sub-differentials $(\gamma_{\tau_n}) \subset (\partial_S \phi(\mu_{\tau_n}))$ converging towards $\partial^\circ \phi(\mu)$ in the W_2 -metric. Pick $\epsilon \in (0, \bar{\epsilon})$ small enough and choose $\mu_\epsilon^{\tau_n} = (\pi^1, \pi^2, \mathcal{G}(\epsilon, \cdot) \circ \pi^1) \# \gamma_{\tau_n} \in \Gamma(\gamma_{\tau_n}, \mathcal{G}(\epsilon, \cdot) \# \mu_{\tau_n})$. By the definition of strong subdifferentials given in (18), it holds that

$$\frac{\phi(\mathcal{G}(\epsilon, \cdot) \# \mu_{\tau_n}) - \phi(\mu_{\tau_n})}{\epsilon} \geq \int_{\mathbb{R}^{2d}} \langle r, \frac{\mathcal{G}(\epsilon, x) - x}{\epsilon} \rangle d\gamma_{\tau_n}(x, r) + o(1). \quad (19)$$

since

$$o(W_{2, \mu}(\mathcal{G}(\epsilon, \cdot) \# \mu_{\tau_n}, \mu_{\tau_n})) = o(\|\mathcal{G}(\epsilon, \cdot) - I_d\|_{L^2(\mathbb{R}^d; \mu_{\tau_n})}) = o(\epsilon) \text{ for all } n \geq 1.$$

Remark that the left hand side of (19) is bounded over $\mathcal{P}(K)$ uniformly with respect to $n \geq 1$ and $\epsilon \in (0, \bar{\epsilon})$ by Lipschitzianity of $\phi(\cdot)$.

We recall that $\gamma_{\tau_n} \xrightarrow{W_2} \partial^\circ \phi(\mu)$ in $\mathcal{P}_2(\mathbb{R}^d \times \mathbb{R}^d)$. Notice that the whole sequence (μ_{τ_n}) is in $\mathcal{P}(K)$, thus for all $\epsilon \in (0, \bar{\epsilon})$ the maps $x \mapsto |(\mathcal{G}(\epsilon, x) - x)/\epsilon|^2$ are uniformly integrable with respect to $\{\pi_{\#}^1 \gamma_{\tau_n}\}_{n=1}^{+\infty}$. Hence, the maps $(x, r) \mapsto |r, (\mathcal{G}(\epsilon, x) - x)/\epsilon|$ are uniformly integrable with respect to $\{\gamma_n\}_{n=1}^{+\infty}$ and the application of Proposition 13-(i) implies that for all $\epsilon \in (0, \bar{\epsilon})$,

$$\int_{\mathbb{R}^{2d}} \langle r, \frac{\mathcal{G}(\epsilon, x) - x}{\epsilon} \rangle d\gamma_{\tau_n}(x, r) \xrightarrow{\tau_n \downarrow 0} \int_{\mathbb{R}^{2d}} \langle r, \frac{\mathcal{G}(\epsilon, x) - x}{\epsilon} \rangle d(\partial^\circ \phi(\mu))(x, r) = \int_{\mathbb{R}^d} \langle \bar{\gamma}^\circ(x), \frac{\mathcal{G}(\epsilon, x) - x}{\epsilon} \rangle d\mu(x) \quad (20)$$

using the notion of *barycenter* of a plan introduced in Definition 16.

Moreover, the Lipschitz regularity in the W_1 -metric of $\phi(\cdot)$ over $\mathcal{P}(K)$ together with Proposition 13-(ii) imply that

$$\phi(\mathcal{G}(\epsilon, \cdot) \# \mu_{\tau_n}) \longrightarrow \phi(\mathcal{G}(\epsilon, \cdot) \# \mu). \quad (21)$$

Thus, merging (19),(20) and (21), we prove that for any $\epsilon \in (0, \bar{\epsilon})$ with $\bar{\epsilon} > 0$ small enough, it holds

$$\frac{\phi(\mathcal{G}(\epsilon, \cdot) \# \mu) - \phi(\mu)}{\epsilon} \geq \int_{\mathbb{R}^d} \langle \bar{\gamma}^\circ(x), \frac{\mathcal{G}(\epsilon, x) - x}{\epsilon} \rangle d\mu(x) + o(1).$$

Invoking similar arguments, the family of maps $(|\langle \bar{\gamma}^\circ(\cdot), (\mathcal{G}(\epsilon, \cdot) - I_d)/\epsilon \rangle|)_{\epsilon \in (0, \bar{\epsilon})}$ is uniformly integrable with respect to μ and it holds that $|\langle \bar{\gamma}^\circ(\cdot), \mathcal{F}(\cdot) \rangle| < +\infty$ μ -almost everywhere. Therefore, letting $\epsilon \downarrow 0$ and invoking Proposition 13-(iii), we recover that

$$\lim_{\epsilon \downarrow 0} \left[\frac{\phi(\mathcal{G}(\epsilon, \cdot) \# \mu) - \phi(\mu)}{\epsilon} \right] \geq \int_{\mathbb{R}^d} \langle \bar{\gamma}^\circ(x), \mathcal{F}(x) \rangle d\mu(x),$$

Following the same steps with $\epsilon \in (-\bar{\epsilon}, 0)$, we obtain the converse inequality for $\epsilon \uparrow 0$. Since we assumed that $\epsilon \mapsto \phi(\mathcal{G}(\epsilon, \cdot) \# \mu)$ is differentiable at $\epsilon = 0$ by **(D)**, these limits coincide and it holds

$$\frac{d}{d\epsilon} [\phi(\mathcal{G}(\epsilon, \cdot) \# \mu)]_{\epsilon=0} = \int_{\mathbb{R}^d} \langle \bar{\gamma}^\circ(x), \mathcal{F}(x) \rangle d\mu(x),$$

which proves our claim. \square

Remark 22 (The case $\partial_S \phi(\mu) \neq \emptyset$). *When $\partial_S \phi(\mu)$ is non-empty, the previous chain rule can be applied with any strong subdifferential and for more general classes of vector fields, see e.g. [5, Remark 10.3.2].*

The interest of proving this kind of result for the minimal selection is twofold. First, as recalled in Theorem 3, a minimal selection always exists when the extended subdifferential is non-empty. Second, minimal selections can be computed explicitly even in very general settings for a wide range of functionals (see e.g. [5, Chapter 10.4] or Section 1.1). In such cases, it is usually induced by its barycenter, yielding the existence of a Wasserstein gradient for the functional.

2.4 Directional derivatives of non-local flows

In this section, we prove the existence of directional derivatives along measure curves generated by suitable Lipschitz families of continuous and bounded maps for non-local flows. Such derivatives are characterized as the only solution of a linearised Cauchy problem. This result can be seen as a generalization to the Wasserstein setting of Proposition 17 and will be useful in the proof of Theorem 1 in Section 3.2.

Before stating our result, we recall the classical Banach Fixed Point Theorem with parameter (see e.g. [10, Theorem A.2.1]).

Theorem 4 (Banach fixed point theorem with parameter). *Let X be a Banach space, S be a metric space and $\Lambda : X \times S \rightarrow X$ be a continuous mapping such that, for some $\kappa < 1$,*

$$\|\Lambda(x, s) - \Lambda(y, s)\|_X \leq \kappa \|x - y\|_X \quad \text{for all } x, y \in X \text{ and } s \in S.$$

Then for each $s \in S$, there exists a unique fixed point $x(s) \in X$ of $\Lambda(\cdot, s)$. Moreover, the map $s \mapsto x(s)$ is continuous for any $s \in S$ and $y \in X$ it holds

$$\|y - x(s)\|_X \leq \frac{1}{1 - \kappa} \|y - \Lambda(s, y)\|_X. \quad (22)$$

Theorem 5 (Directional derivative of a non-local flow with respect to the initial data). *Let $\mu \in \mathcal{P}_c(\mathbb{R}^d)$, $\bar{\epsilon} > 0$ be a small parameter, $\mathcal{G}(\cdot, \cdot) \in \text{Lip}((-\bar{\epsilon}, \bar{\epsilon}), C^0(\mathbb{R}^d, \mathbb{R}^d))$ be a family of bounded maps with $\mathcal{G}(0, \cdot) = I_d$ and $\mathcal{F} : x \in \text{supp}(\mu) \mapsto \frac{d}{d\epsilon} [\mathcal{G}(\epsilon, x)]_{\epsilon=0}$ be continuous as well.*

*Let $v[\cdot](\cdot, \cdot)$ be a non-local vector field satisfying hypotheses **(F)**, **(B)**, **(D)**, $\Phi_{(0, \cdot)}^v\cdot$ be the corresponding family of non-local flows as defined in Theorem 2 and $\mu(\cdot)$ be the unique solution of the corresponding Cauchy problem (15) starting from μ .*

Then, the map $\epsilon \in (-\bar{\epsilon}, \bar{\epsilon}) \mapsto \Phi_{(0, t)}^v[\mathcal{G}(\epsilon, \cdot)]_{\#} \mu(x)$ admits a derivative at $\epsilon = 0$ for all $(t, x) \in [0, T] \times \overline{B(0, R_T)}$ that we denote by $w_{\Phi}(t, x)$. It can be characterised as the unique solution to the Cauchy problem

$$\begin{cases} \partial_t w(t, x) = D_x v[\mu(t)] \left(t, \Phi_{(0, t)}^v[\mu](x) \right) w(t, x) \\ \quad + \int_{\mathbb{R}^d} \Pi_{(t, \Phi_{(0, t)}^v[\mu](x))}^{\circ} \left(\Phi_{(0, t)}^v[\mu](y) \right) \cdot [D_x \Phi_{(0, t)}[\mu](y) \mathcal{F}(y) + w(t, y)] d\mu(y), \\ w(0, x) = 0 \end{cases} \quad (23)$$

where for all (t, z) , $\Pi_{(t, z)}^{\circ}(\cdot)$ is the matrix-valued map made of the barycenters of the minimal selections $\partial_{\mu}^{\circ} v^i[\mu^(t)](t, z)$ in the extended subdifferential of the components of $\mu \mapsto v^i[\mu](t, z)$ at $\mu^*(t)$.*

Proof. We follow a classical scheme of proof used in the finite dimensional setting to show that flows of diffeomorphisms admit directional derivatives characterized as the unique solution of a linearised Cauchy problem (see e.g. [10, Theorem 2.3.1]).

First, we define $\Omega = B(0, R_T)$ and we introduce the operator $\Lambda_{\Phi} : w \in C^0([0, T] \times \Omega, \mathbb{R}^d) \mapsto \Lambda_{\Phi}(w) \in C^0([0, T] \times \Omega, \mathbb{R}^d)$ defined for all $(t, x) \in [0, T] \times \Omega$ by

$$\begin{aligned} \Lambda_{\Phi}(w)(t, x) &= x + \int_0^t D_x v[\mu(s)] \left(s, \Phi_{(0, s)}^v[\mu](x) \right) w(s, x) ds \\ &\quad + \int_0^t \int_{\mathbb{R}^d} \Pi_{(s, \Phi_{(0, s)}^v[\mu](x))}^{\circ} \left(\Phi_{(0, s)}^v[\mu](y) \right) \cdot [D_x \Phi_{(0, s)}[\mu](y) \mathcal{F}(y) + w(s, y)] d\mu(y) ds. \end{aligned}$$

We want to show that this operator admits a unique fixed point. Afterwards, we prove that it coincides with the map which to every (t, x) associates the derivative at $\epsilon = 0$ of the family of non-local

flows $\epsilon \mapsto \Phi_{(0,t)}^v[\mathcal{G}(\epsilon, \cdot) \# \mu](x)$. With this goal, we introduce a parameter $\alpha > 0$ that will be chosen so that $\Lambda_\Phi(\cdot)$ is contractive with respect to the equivalent norm

$$\|w\|_{C^0([0,T] \times \Omega)}^\alpha = \sup_{(t,x) \in [0,T] \times \Omega} [e^{-2\alpha t} |w(t,x)|]. \quad (24)$$

Remark that for any $w_1, w_2 \in C^0([0, T] \times \Omega, \mathbb{R}^d)$ and any $(t, x) \in [0, T] \times \Omega$, it holds

$$\begin{aligned} |\Lambda_\Phi(w_2)(t, x) - \Lambda_\Phi(w_1)(t, x)| &\leq \int_0^t \left| \mathbb{D}_x v[\mu(s)] \left(s, \Phi_{(0,s)}^v[\mu](x) \right) \cdot (w_2(s, x) - w_1(s, x)) \right| ds \\ &+ \int_0^t \int_{\mathbb{R}^d} \left| \mathbb{I}^\circ_{(s, \Phi_{(0,s)}^v[\mu](x))} \left(\Phi_{(0,s)}^v[\mu](y) \right) \cdot (w_2(s, y) - w_1(s, y)) \right| d\mu(y) ds \\ &\leq \int_0^t (L_1 |w_2(s, x) - w_1(s, x)| + L_2 \|w_2(s, \cdot) - w_1(s, \cdot)\|_{L^1(\mu)}) ds \\ &\leq \int_0^t (L_1 + L_2) \|w_2(s, \cdot) - w_1(s, \cdot)\|_{C^0(\Omega)} ds \\ &\leq \int_0^t e^{2\alpha s} (L_1 + L_2) \|w_2(\cdot, \cdot) - w_1(\cdot, \cdot)\|_{C^0([0,T] \times \Omega)}^\alpha ds \\ &\leq \frac{e^{2\alpha t} - 1}{2\alpha} (L_1 + L_2) \|w_2(\cdot, \cdot) - w_1(\cdot, \cdot)\|_{C^0([0,T] \times \Omega)}^\alpha. \end{aligned}$$

since $\mu(\Omega) = 1$. Here, we choose

$$L_1 = \left\| \mathbb{D}_x v[\mu(\cdot)](\cdot, \Phi_{(0,\cdot)}^v[\mu](\cdot)) \right\|_{C^0([0,T] \times \Omega)} \quad \text{and} \quad L_2 = \left\| \mathbb{I}^\circ_{(\cdot, \Phi_{(0,\cdot)}^v[\mu](\cdot))}(\cdot) \right\|_{C^0([0,T] \times \Omega)},$$

which exists by hypotheses **(F)** and **(B)**. Multiplying both sides of the inequality by $e^{-2\alpha t}$ and taking the supremum over (t, x) in the left-hand side yields the desired contractivity with a constant equal to $1/2$ provided that $\alpha \geq (L_1 + L_2)$. It is then possible to apply Theorem 4 to obtain the existence of a unique fixed point $w_\Phi(\cdot, \cdot) \in C^0([0, T] \times \Omega, \mathbb{R}^d)$ of $\Lambda_\Phi(\cdot)$.

Define for $\epsilon \in (-\bar{\epsilon}, \bar{\epsilon})$ the parametrized family of operators $\Psi^\epsilon(\cdot) : f \in C^0([0, T] \times \Omega, \mathbb{R}^d) \mapsto \Psi^\epsilon(f) \in C^0([0, T] \times \Omega, \mathbb{R}^d)$ defined by

$$\Psi^\epsilon(f)(t, x) = x + \int_0^t v[f(s, \cdot) \# (\mathcal{G}(\epsilon, \cdot) \# \mu)](s, f(s, x)) ds. \quad (25)$$

for all $(t, x) \in [0, T] \times \Omega$. Up to defining again the equivalent norm $\|\cdot\|_{C^0([0,T] \times \Omega)}^\alpha$ as in (24) with a suitable $\alpha > 0$, it can be shown that this operator is contractive independently from ϵ as a direct consequence of the Lipschitzianity hypotheses given in **(F)**. We can thus invoke again Theorem 4 to obtain the existence of a unique fixed point of $\Psi^\epsilon(\cdot)$ for each $\epsilon \in (-\bar{\epsilon}, \bar{\epsilon})$. Notice that by definition, this family of fixed points is precisely the parametrized family of non-local flows $(t, x) \mapsto \Phi_{(0,t)}^v[\mathcal{G}(\epsilon, \cdot) \# \mu](x)$.

We now define the map $\hat{\Phi}_{(0,\cdot)}^{v,\epsilon}[\mu](\cdot)$ by

$$\hat{\Phi}_{(0,\cdot)}^{v,\epsilon}[\mu](\cdot) : (t, x) \mapsto \Phi_{(0,t)}^v[\mu](x) + \epsilon w_\Phi(t, x).$$

To conclude, we then need to show that

$$\lim_{\epsilon \rightarrow 0} \left\| \frac{1}{\epsilon} \left(\hat{\Phi}_{(0,\cdot)}^{v,\epsilon}[\mu](\cdot) - \Phi_{(0,\cdot)}^v[\mathcal{G}(\epsilon, \cdot) \# \mu](\cdot) \right) \right\|_{C^0([0,T] \times \Omega)} = 0,$$

which will directly yield the existence and the characterization of the directional derivative of the flow along $(-\bar{\epsilon}, \bar{\epsilon}) \mapsto \mathcal{G}(\epsilon, \cdot)$. By (22) in Theorem 4 and the equivalence of the C^0 -norms we introduced, there exists a constant $C > 0$ independent from ϵ such that it holds

$$\frac{1}{|\epsilon|} \left\| \hat{\Phi}_{(0,\cdot)}^{v,\epsilon}[\mu](\cdot) - \Phi_{(0,\cdot)}^v[\mathcal{G}(\epsilon, \cdot) \# \mu](\cdot) \right\|_{C^0} \leq \frac{2C}{|\epsilon|} \left\| \hat{\Phi}_{(0,\cdot)}^{v,\epsilon}[\mu](\cdot) - \Psi^\epsilon(\hat{\Phi}_{(0,\cdot)}^{v,\epsilon}[\mu](\cdot))(\cdot, \cdot) \right\|_{C^0}.$$

Take now $(s, x) \in [0, T] \times \Omega$. One has by definition of $\hat{\Phi}_{(0,\cdot)}^{v,\epsilon}[\mu](\cdot)$ that

$$\begin{aligned} \hat{\Phi}_{(0,s)}^{v,\epsilon}[\mu](\mathcal{G}(\epsilon, x)) &= \Phi_{(0,s)}^v[\mu](\mathcal{G}(\epsilon, x)) + \epsilon w_\Phi(s, \mathcal{G}(\epsilon, x)) \\ &= \Phi_{(0,s)}^v[\mu](x) + \epsilon \left(\mathbb{D}_x \Phi_{(0,s)}^v[\mu](x) \mathcal{F}(x) + w_\Phi(s, x) \right) + o(\epsilon), \end{aligned}$$

by continuity of $w_\Phi(s, \cdot)$ for all $s \in [0, T]$

By assumptions **(F)**, **(B)** and **(D)**, we can apply the chain rule of Proposition 21 component-wise on the v^i to obtain that

$$\begin{aligned} v \left[\hat{\Phi}_{(0,s)}^{v,\epsilon}[\mu](\cdot) \circ \mathcal{G}(\epsilon, \cdot) \# \mu \right] (s, z) &= v[\Phi_{(0,s)}^v[\mu](\cdot) \# \mu](s, z) \\ &+ \epsilon \int_{\mathbb{R}^d} \Pi_{(s,z)}^\circ \left(\Phi_{(0,s)}^v[\mu](y) \right) \left[D_x \Phi_{(0,s)}^v[\mu](y) \mathcal{F}(y) + w_\Phi(s, y) \right] d\mu(y) + o(\epsilon) \end{aligned} \quad (26)$$

where for all (s, z) the map $y \mapsto \Pi_{(s,z)}^\circ(y) = (\bar{\gamma}_{(s,z)}^{i,\circ}(y))_{1 \leq i \leq d} \in \mathbb{R}^{d \times d}$ is made of the barycenters of the minimal selections in the extended subdifferentials of the v^i 's.

Performing a Taylor expansion in the space variable for the non-local velocity field, it also holds that

$$\begin{aligned} v \left[\Phi_{(0,s)}^v[\mu](\cdot) \# \mu \right] \left(s, \Phi_{(0,s)}^v[\mu](x) + \epsilon w_\Phi(s, x) \right) &= v[\Phi_{(0,s)}^v[\mu](\cdot) \# \mu] \left(s, \Phi_{(0,s)}^v[\mu](x) \right) \\ &+ \epsilon D_x v[\Phi_{(0,s)}^v[\mu](\cdot) \# \mu] \left(s, \Phi_{(0,s)}^v[\mu](x) \right) \cdot w_\Phi(s, x) + o(\epsilon), \end{aligned} \quad (27)$$

as well as

$$\Pi_{(s, \Phi_{(0,s)}^v[\mu](x) + \epsilon w_\Phi(s, x))}^\circ \left(\Phi_{(0,s)}^v[\mu](y) \right) = \Pi_{(s, \Phi_{(0,s)}^v[\mu](x))}^\circ \left(\Phi_{(0,s)}^v[\mu](y) \right) + o(1) \quad (28)$$

thanks to assumption **(B)** in which we state that $z \mapsto \Pi_{(t,z)}^\circ(x)$ is continuous for all $(s, x) \in [0, T] \times \mathbb{R}^d$.

Merging (25), (26) and (27), (28) and recalling the definition of $w_\Phi(\cdot, \cdot)$, it holds

$$\begin{aligned} \Psi^\epsilon \left(\hat{\Phi}_{(0,\cdot)}^{v,\epsilon}[\mu](\cdot) \right) (t, x) &= x + \int_0^t v[\Phi_{(0,s)}^v[\mu](\cdot) \# \mu](s, \Phi_{(0,s)}^v[\mu](x)) ds \\ &+ \epsilon \int_0^t D_x v[\Phi_{(0,s)}^v[\mu](\cdot) \# \mu](s, \Phi_{(0,s)}^v[\mu](x)) \cdot w_\Phi(s, x) ds \\ &+ \epsilon \int_0^t \int_{\mathbb{R}^d} \Pi_{(s, \Phi_{(0,s)}^v[\mu](x))}^\circ \left(\Phi_{(0,s)}^v[\mu](y) \right) \left[D_x \Phi_{(0,s)}^v[\mu](y) \mathcal{F}(y) + w_\Phi(s, y) \right] d\mu(y) ds + o(\epsilon) \\ &= \Phi_{(0,t)}^v[\mu](x) + \epsilon w_\Phi(t, x) + o(\epsilon). \end{aligned}$$

Therefore, we finally recover that

$$\frac{1}{|\epsilon|} \left| \Psi^\epsilon(\hat{\Phi}_{(0,\cdot)}^\epsilon[\mu](\cdot))(t, x) - \hat{\Phi}_{(0,t)}^\epsilon[\mu](x) \right| \leq o(1) \quad \text{as } \epsilon \rightarrow 0 \text{ for all } (t, x) \in [0, T],$$

and conclude that

$$\lim_{\epsilon \rightarrow 0} \left[\left\| \frac{1}{\epsilon} \left(\Phi_{(0,\cdot)}[\mathcal{G}(\epsilon, \cdot) \# \mu](\cdot) - \hat{\Phi}_{(0,\cdot)}^\epsilon[\mu](\cdot) \right) \right\|_{C^0([0,T] \times \Omega)} \right] = 0.$$

We thus proved that the derivative of $\epsilon \in (-\bar{\epsilon}, \bar{\epsilon}) \mapsto \Phi_{(0,t)}^v[\mathcal{G}(\epsilon, \cdot) \# \mu](x)$ at $\epsilon = 0$ exists for any (t, x) and that it is the only solution of equation (23). \square

3 The Pontryagin Maximum Principle

In this section, we prove the main result of our article, that is the Pontryagin Maximum Principle in the Wasserstein space. We first describe the proof for a simplified problem (\mathcal{P}_1) with no interaction field $v[\cdot](\cdot, \cdot)$ and no running cost $L(\cdot, \cdot)$ in Section 3.1. We then proceed to prove the PMP for the more general problem (\mathcal{P}) in Section 3.2. In what follows, we shall restrict our attention to the Wasserstein space $\mathcal{P}_c(\mathbb{R}^d)$ endowed with the W_2 -metric.

3.1 The Pontryagin Maximum Principle with no interaction field and no running cost

We start by proving the Pontryagin Maximum Principle for a simplified version of the optimal control problem (\mathcal{P}) presented in the Introduction. We consider the following optimal control problem in the space of probability measures

$$(\mathcal{P}_1) \quad \begin{cases} \min_{u \in \mathcal{U}} [\varphi(\mu(T))], \\ \text{s.t.} \quad \begin{cases} \partial_t \mu(t) + \nabla \cdot (u(t)\mu(t)) = 0, \\ \mu(0) = \mu^0 \in \mathcal{P}_c(\mathbb{R}^d), \end{cases} \end{cases} \quad (29)$$

and show the Pontryagin-type optimality conditions provided in the following theorem.

Theorem 6 (Pontryagin Maximum Principle for (\mathcal{P}_1)). *Let $(u^*(\cdot), \mu^*(\cdot)) \in \mathcal{U} \times \text{Lip}([0, T], \mathcal{P}_c(\mathbb{R}^d))$ be an optimal pair control-trajectory for (\mathcal{P}_1) and assume that hypotheses **(U)**, **(C)**, **(B)** hold. Then, there exists a constant $R > 0$ and a curve $\nu^*(\cdot) \in \text{Lip}([0, T], \mathcal{P}(\overline{B_{2d}(0, R)}))$ satisfying the following statements :*

(i) *It solves the forward-backward system of continuity equations*

$$\begin{cases} \partial_t \nu^*(t) + \nabla_{(x,r)} \cdot (\mathbb{J}_{2d} \nabla_{\nu} \mathbb{H}_c(\nu^*(t), u^*(t)) \nu^*(t)) = 0, & \text{in } [0, T] \times \mathbb{R}^{2d} \\ \pi_{\#}^1 \nu^*(0) = \mu^0, \\ \pi_{\#}^2 \nu^*(T) = (-\bar{\gamma}_{\varphi}^{\circ})_{\#} \mu^*(T), \end{cases} \quad (30)$$

where \mathbb{J}_{2d} is the symplectic matrix of \mathbb{R}^{2d} .

The compactified Hamiltonian $\mathbb{H}_c(\cdot, \cdot)$ of the system is defined by

$$\mathbb{H}_c : (\nu, \omega) \in \mathcal{P}_c(\mathbb{R}^{2d}) \times U \mapsto \begin{cases} \mathbb{H}(\nu, \omega) & \text{if } \nu \in \mathcal{P}(\overline{B_{2d}(0, R)}) \\ + \infty & \text{otherwise} \end{cases}, \quad (31)$$

where

$$\mathbb{H} : (\nu, \omega) \in \mathcal{P}_c(\mathbb{R}^{2d}) \times U \mapsto \int_{\mathbb{R}^{2d}} \langle r, \omega(x) \rangle d\nu(x, r) \quad (32)$$

is the infinite dimensional Hamiltonian of the system.

The vector field $(x, r) \mapsto \nabla_{\nu} \mathbb{H}_c(\nu^*(t), u^*(t))(x, r) = (D_x u^*(t, x)^{\top} r, u^*(t, x))$ is the Wasserstein gradient of the compactified Hamiltonian for \mathcal{L}^1 -almost every $t \in [0, T]$, i.e. $\partial_{\nu}^{\circ} \mathbb{H}_c(\nu^*(t), u^*(t)) = (I_d \times \nabla_{\nu} \mathbb{H}_c(\nu^*(t), u^*(t))(\cdot, \cdot))_{\#} \nu^*(t)$.

(ii) *It satisfies the Pontryagin maximization condition*

$$\mathbb{H}_c(\nu^*(t), u^*(t)) = \max_{\omega \in U} [\mathbb{H}_c(\nu^*(t), \omega)] \quad \text{holds for almost every } t \in [0, T]. \quad (33)$$

We split the proof of this result into several steps. In Step 1, we introduce the concept of needle-like variation and compute explicitly the corresponding family of perturbed measures. In Step 2 we study the first order perturbation of the final cost induced by the needle-like variation. We introduce in Step 3 a suitable costate propagating this information backward to the base point of the needle-variation. In Step 4, we show that the curve introduced in Step 3 satisfies the conditions (i) and (ii) of the PMP.

Step 1 : Needle-like variations

We start by considering an optimal pair control-trajectory $(u^*(\cdot), \mu^*(\cdot)) \in \mathcal{U} \times \text{Lip}([0, T], \mathcal{P}_c(\mathbb{R}^d))$ along with the constant $R_T > 0$ such that $\text{supp}(\mu(t)) \subset \overline{B(0, R_T)}$ for all times $t \in [0, T]$. Fix a control $\omega \in U$, a Lebesgue point $\tau \in [0, T]$ of $t \mapsto u^*(t) \in C^1(\mathbb{R}^d, \mathbb{R}^d)$ in the Bochner sense (see, e.g. [16]) and a parameter $\epsilon \in [0, \bar{\epsilon})$ with $\bar{\epsilon} > 0$ small. We define the *needle-like variation* of parameters (ω, τ, ϵ) of u^* as follows

$$\tilde{u}_{\epsilon}^{\omega, \tau} \equiv \tilde{u}_{\epsilon} : t \mapsto \begin{cases} \omega & \text{if } t \in [\tau - \epsilon, \tau], \\ u^*(t) & \text{otherwise.} \end{cases} \quad (34)$$

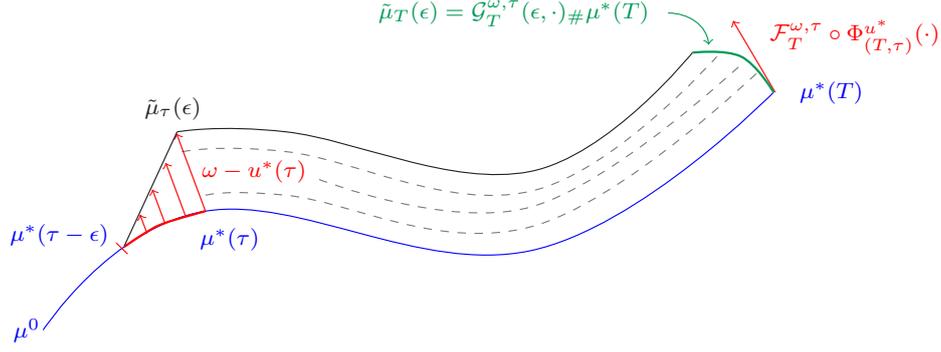


Figure 1: *Illustration of the effect of a needle-like variation on a measure curve.*

We denote by $t \mapsto \tilde{\mu}_t(\epsilon)$ the corresponding solution of the continuity equation starting from μ^0 at time $t = 0$. Notice that $\tilde{u}_\epsilon(\cdot) \in L^1([0, T], C^1(\mathbb{R}^d, \mathbb{R}^d)) \cap L^\infty(\mathbb{R}^d, \mathbb{R}^d)$, thus the corresponding continuity equation is still well-posed.

The link between the perturbed measure $\tilde{\mu}_T(\epsilon)$ and the optimal measure $\mu^*(T)$ at time T is given in the following Lemma.

Lemma 23. *There exists a family of functions $\mathcal{G}_T^{\omega, \tau}(\cdot, \cdot) \in \text{Lip}((-\bar{\epsilon}, \bar{\epsilon}), C^0(\mathbb{R}^d, \mathbb{R}^d))$ such that they are C^1 -diffeomorphisms over $\overline{B(0, R_T)}$ for all $\epsilon \geq 0$ and it holds*

$$\tilde{\mu}_T(\epsilon) = \mathcal{G}_T^{\omega, \tau}(\epsilon, \cdot) \# \mu^*(T). \quad (35)$$

Moreover, there exists a constant $R_T^\Phi > 0$ depending on R_T, L_U and $\text{Lip}(\Phi_t^v(\cdot), \overline{B(0, R_T)})$ such that for all $\epsilon \in (-\bar{\epsilon}, \bar{\epsilon})$ it holds $\text{supp}(\mathcal{G}_T^{\omega, \tau}(\epsilon, \cdot) \# \mu^*(T)) \subset \overline{B(0, R_T^\Phi)}$.

This family of maps satisfies the following Taylor expansion with respect to the $L^2(\mathbb{R}^d, \mathbb{R}^d; \mu^*(T))$ -norm

$$\mathcal{G}_T^{\omega, \tau}(\epsilon, \cdot) = I_d + \epsilon \mathcal{F}_T^{\omega, \tau} \circ \Phi_{(T, \tau)}^{u^*}(\cdot) + o(\epsilon),$$

where

$$\mathcal{F}_T^{\omega, \tau} : x \in \text{supp}(\mu^*(\tau)) \mapsto D_x \Phi_{(\tau, T)}^{u^*}(x) \cdot [\omega(x) - u^*(\tau, x)] \quad (36)$$

is a C^0 mapping.

Proof. By definition of $\tilde{u}_\epsilon(\cdot, \cdot)$ in (34), it holds that

$$\tilde{\mu}_T(\epsilon) = \Phi_{(\tau, T)}^{u^*} \circ \Phi_{(\tau-\epsilon, \tau)}^\omega \circ \Phi_{(\tau, \tau-\epsilon)}^{u^*} \circ \Phi_{(T, \tau)}^{u^*}(\cdot) \# \mu^*(T) \text{ for all } \epsilon \in [0, \bar{\epsilon}].$$

Thus, by choosing $\mathcal{G}_T^{\omega, \tau}(\epsilon, \cdot) = \Phi_{(\tau, T)}^{u^*} \circ \Phi_{(\tau-\epsilon, \tau)}^\omega \circ \Phi_{(\tau, \tau-\epsilon)}^{u^*} \circ \Phi_{(T, \tau)}^{u^*}(\cdot)$, formula (35) holds true for $\epsilon \in [0, \bar{\epsilon}]$. Moreover, since the definition of $\epsilon \mapsto \mathcal{G}_T^{\omega, \tau}(\epsilon, \cdot)$ only involves functions that are continuous and uniformly bounded over $\overline{B(0, R_T)}$, the perturbed measures $\tilde{\mu}_T(\cdot)$ are compactly supported in some bigger ball $\overline{B(0, R_T')}$ for all $\epsilon \in [0, \bar{\epsilon}]$ as well.

Recalling the definition of the flow $x \mapsto \Phi_{(0, t)}^v(x)$, one has by Lebesgue's Differentiation Theorem (see e.g. [18, Chapter 1.7]) :

$$\begin{cases} \Phi_{(\tau, \tau-\epsilon)}^{u^*}(x) = x - \int_{\tau-\epsilon}^{\tau} u^*(t, \Phi_{(\tau, t)}^{u^*}(x)) dt = x - \epsilon u^*(\tau, x) + o(\epsilon) \\ \Phi_{(\tau-\epsilon, \tau)}^\omega(x) = x + \int_{\tau-\epsilon}^{\tau} \omega(\Phi_{(\tau-\epsilon, t)}^\omega(x)) dt = x + \epsilon \omega(x) + o(\epsilon) \end{cases}$$

since $t \mapsto \Phi_{\tau-\epsilon, t}^{u^*}(x)$ and $t \mapsto \Phi_{t, \tau}^{u^*}(x)$ are C^0 for any x and τ is a Lebesgue point of $t \mapsto u^*(t) \in C^1(\mathbb{R}^d, \mathbb{R}^d)$ in the Bochner sense. Chaining these two expansions and recalling that $\omega(\cdot)$ and $\Phi_{(\tau, T)}^{u^*}(\cdot)$ are C^1 -smooth yields

$$\Phi_{(\tau, T)}^{u^*} \circ \Phi_{(\tau-\epsilon, \tau)}^\omega \circ \Phi_{(\tau, \tau-\epsilon)}^{u^*}(x) = \Phi_{(\tau, T)}^{u^*}(x) + \epsilon D_x \Phi_{(\tau, T)}^{u^*}(x) \cdot [\omega(x) - u^*(\tau, x)] + o(\epsilon).$$

Thus

$$\mathcal{G}_T^{\omega, \tau}(\epsilon, x) = x + \epsilon \mathcal{F}_T^{\omega, \tau} \circ \Phi_{(T, \tau)}^{u^*}(x) + o(\epsilon) \text{ for any } x \in \text{supp}(\mu^*(T)),$$

where we choose

$$\mathcal{F}_T^{\omega, \tau} : x \mapsto D_x \Phi_{(\tau, T)}^{u^*}(x) \cdot [\omega(x) - u^*(\tau, x)].$$

We can now extend $\mathcal{G}_T^{\omega, \tau}(\cdot, \cdot)$ from $[0, \bar{\epsilon}]$ to $(-\bar{\epsilon}, \bar{\epsilon})$ in such a way that the left and right derivatives at $\epsilon = 0$ coincide, by defining e.g.

$$\mathcal{G}_T^{\omega, \tau}(\epsilon, \cdot) \equiv I_d + \epsilon \mathcal{F}_T^{\omega, \tau} \circ \Phi_{(T, \tau)}^{u^*}(\cdot)$$

whenever $\epsilon \in (-\bar{\epsilon}, 0]$. Notice that since $\mathcal{F}_T^{\omega, \tau} \circ \Phi_{(T, \tau)}^{u^*}(\cdot)$ is C^0 , both $x \in \overline{B(0, R_T)} \mapsto \mathcal{G}_T^{\omega, \tau}(\epsilon, x)$ and $x \in \overline{B(0, R_T)} \mapsto \frac{d}{d\epsilon} [\mathcal{G}_T^{\omega, \tau}(\epsilon, x)]_{\epsilon=0}$ define C^0 mappings for all $\epsilon \in (-\bar{\epsilon}, \bar{\epsilon})$. Moreover, the continuity and uniform boundedness of $D_x \Phi_{(\tau, T)}^{u^*}(\cdot)$ over $\overline{B(0, R_T)}$ along with hypothesis **(U)** imply that $\mathcal{F}_T^{\omega, \tau}(\cdot)$ is bounded. Hence, there exists a constant $R_T^\Phi > 0$ such that $\text{supp}(\mathcal{G}_T^{\omega, \tau}(\epsilon, \cdot)_{\#} \mu^*(T)) \subset \overline{B(0, R_T^\Phi)}$ for all $\epsilon \in (-\bar{\epsilon}, \bar{\epsilon})$. Moreover, the fact that $\mathcal{G}(\epsilon, \cdot)$ and $\mathcal{F}_T^{\omega, \tau}(\cdot)$ are continuous and bounded yields that they are uniformly integrable with respect to the compactly supported measure $\mu^*(T)$. An application of Proposition 13–(iii) allows to conclude that this expansion holds in $L^2(\mathbb{R}^d, \mathbb{R}^d; \mu^*(T))$, which achieves the proof. \square

We end this first step by a Lemma which is a direct consequence of Proposition 17.

Lemma 24. *For any $x \in \text{supp}(\mu^*(\tau))$, the trajectory $t \mapsto \mathcal{F}_t^{\omega, \tau}(x)$ is the unique solution of the Cauchy problem*

$$\partial_t \mathcal{F}_t^{\omega, \tau}(x) = D_x u^*\left(t, \Phi_{(\tau, t)}^{u^*}(x)\right) \mathcal{F}_t^{\omega, \tau}(x), \quad \mathcal{F}_\tau^{\omega, \tau}(x) = \omega(x) - u^*(\tau, x). \quad (37)$$

Proof. It is sufficient to apply Proposition 17 and to remark that here $v(\cdot) \equiv u^*(\cdot)$. \square

Step 2 : First-order optimality condition

Thanks to the optimality of $u^*(\cdot)$, for each $\epsilon \in (0, \bar{\epsilon})$ it holds

$$\frac{\varphi(\tilde{\mu}_T(\epsilon)) - \varphi(\mu^*(T))}{\epsilon} \geq 0, \quad (38)$$

where $\epsilon \in (0, \bar{\epsilon}) \mapsto \tilde{\mu}_T(\epsilon) = \mathcal{G}_T^{\omega, \tau}(\epsilon, \cdot)_{\#} \mu^*(T)$.

Recalling that the measures $\epsilon \mapsto \tilde{\mu}_T(\epsilon)$ are uniformly compactly supported, that $\varphi(\cdot)$ satisfies hypotheses **(C)** and that the map $\epsilon \in (-\bar{\epsilon}, \bar{\epsilon}) \mapsto \varphi(\tilde{\mu}_T(\epsilon))$ is differentiable at $\epsilon = 0$ by hypothesis **(D)**, we can apply the chainrule given in Proposition 21 to the endpoint cost :

$$0 \leq \lim_{\epsilon \downarrow 0} \left[\frac{\varphi(\tilde{\mu}_T(\epsilon)) - \varphi(\mu^*(T))}{\epsilon} \right] = \int_{\mathbb{R}^d} \langle \bar{\gamma}_\varphi^\circ(x), \mathcal{F}_T^{\omega, \tau} \circ \Phi_{(T, \tau)}^{u^*}(x) \rangle d\mu^*(T)(x), \quad (39)$$

where $\bar{\gamma}_\varphi^\circ \in L^2(\mathbb{R}^d, \mathbb{R}^d; \mu^*(T))$ is the barycenter of the minimal selection $\partial^\circ \varphi(\mu^*(T))$ in the extended subdifferential of $\varphi(\cdot)$ at $\mu^*(T)$.

We recover a formula similar to the classical finite dimensional case. The next step is to introduce a suitable *costate* along with its backward dynamics that will *propagate* this first-order information to the base-point τ of the needle-like variation while generating a Hamiltonian-like dynamical structure.

Step 3 : Backward dynamics and Pontryagin maximization condition

Equation (39) provides us with a first-order optimality condition which involves all the needle parameters $(\omega, \tau) \in U \times [0, T]$. We will show that it implies, along with the choice of a suitable costate, the maximization condition (33).

To this aim, we build a curve $\nu^*(\cdot) \in \text{Lip}([0, T], \mathcal{P}_c(\mathbb{R}^{2d}))$ solution of the forward-backward system of continuity equations

$$\begin{cases} \partial_t \nu^*(t) + \nabla \cdot (\mathcal{V}^*(t, \cdot, \cdot)) \nu^*(t) = 0 & \text{in } [0, T] \times \mathbb{R}^{2d}, \\ \pi_{\#}^1 \nu^*(t) = \mu^*(t) & \text{for all } t \in [0, T], \\ \nu^*(T) = (I_d \times (-\bar{\gamma}_\varphi^\circ))_{\#} \mu^*(T), \end{cases} \quad (40)$$

associated to the vector field

$$\mathcal{V}^* : (t, x, r) \in [0, T] \times \mathbb{R}^{2d} \mapsto (u^*(t, x), -D_x u^*(t, x)^\top r). \quad (41)$$

Notice that, contrarily to system (30), we impose the more restrictive product structure on the terminal datum.

This system is peculiar in the sense that the driving vector field $\mathcal{V}^*(\cdot, \cdot, \cdot)$ does not satisfy verbatim the hypotheses **(H')** of Theorem 2. However, it exhibits a *cascade* structure, in the sense that one can first determine uniquely $\mu^*(\cdot)$ and then build $\nu^*(\cdot)$ by disintegration. This fact is underlined by the condition $\pi_{\#}^1 \nu^*(t) = \mu^*(t)$ for all times $t \in [0, T]$. We make this statement precise in the next Lemma.

Lemma 25 (Definition and well-posedness of solutions of (40)). *Let $\mu^*(\cdot)$ be the optimal trajectory for (\mathcal{P}_1) generated by the optimal control $u^*(\cdot) \in \mathcal{U}$. For $\mu^*(T)$ -almost every $x \in \mathbb{R}^d$, we consider the family of flows of diffeomorphisms $(\Phi_{(T,t)}^{B,x}(\cdot))_{t \leq T}$ associated to the Cauchy problem*

$$\partial_t w_x(t, r) = -\text{D}u^*(t, \Phi_{(T,t)}^{u^*}(x))w_x(t, r), \quad w_x(T, r) = -\bar{\gamma}_\varphi^\circ(x), \quad (42)$$

and define the curves of measures $\sigma_x^* : t \mapsto \Phi_{(T,t)}^{B,x}(\cdot)_{\#} \mu^*(T)$.

Define $\nu^* : t \mapsto (\Phi_{(T,t)}^{u^*}(\cdot), I_d)_{\#} \nu_T^*(t)$ where² $\nu_T^*(t) = \int \sigma_x^*(t) d\mu^*(T)(x) \in \mathcal{P}_c(\mathbb{R}^{2d})$ for all times $t \in [0, T]$. Then, $\nu^*(\cdot)$ is the unique solution of (40). Moreover, there exists two constants $R'_T, L'_T > 0$ such that

$$\text{supp}(\nu^*(t)) \subset \overline{B_{2d}(0, R'_T)} \quad \text{and} \quad W_1(\nu^*(t), \nu^*(s)) \leq L'_T |t - s| \quad \text{for all } s, t \in [0, T].$$

Proof. We recall that by hypothesis **(U)**, the elements of \mathcal{U} are uniformly sublinear and Lipschitz in space for \mathcal{L}^1 -almost every times $t \in [0, T]$. We recall that by Theorem 2, this implies the existence of a constant $R_T > 0$ depending on $\text{supp}(\mu^0), T$ and L_U such that $\text{supp}(\mu^*(\cdot)) \subset \overline{B(0, R_T)}$.

For $\mu^*(T)$ -almost every $x \in \mathbb{R}^d$, the Cauchy problem (42) has a unique solution and the corresponding curves $t \mapsto \sigma_x^*(t)$ are uniquely determined. Moreover, the uniform Lipschitzianity of the elements of \mathcal{U} implies that these curves are uniformly compactly supported and Lipschitz in the W_1 -metric uniformly with respect to $x \in \text{supp}(\mu^*(T))$ with constants \bar{R}_T, \bar{L}_T depending on L_U, T and $\varphi(\cdot)$.

We now define the curve $\nu^*(\cdot)$ as in the statement of Lemma 25 above and show that it is a uniformly compactly supported and Lipschitz solution of the forward-backward system (40). The fact that there exists $R_T > 0$ depending on R_T and \bar{R}_T such that $\nu^*(\cdot)$ is uniformly compactly supported in $\overline{B_{2d}(0, R_T)}$ is a direct consequence of its definition. The Lipschitzianity results from the following computations. For any $\xi \in \text{Lip}(\mathbb{R}^{2d}, \mathbb{R})$ with $\text{Lip}(\xi, \mathbb{R}^{2d}) \leq 1$, it holds

$$\begin{aligned} \int_{\mathbb{R}^{2d}} \xi(x, r) d(\nu^*(t) - \nu^*(s))(x, r) &= \int_{\mathbb{R}^d} \int_{\mathbb{R}^d} \xi(\Phi_{(T,t)}^{u^*}(x), r) d(\sigma_x^*(t) - \sigma_x^*(s))(r) d\mu^*(T)(x) \\ &\leq \int_{\mathbb{R}^d} |\Phi_{(T,t)}^{u^*}(x) - \Phi_{(T,s)}^{u^*}(x)| d\mu^*(T)(x) \\ &\quad + \int_{\mathbb{R}^d} \text{Lip}(\Phi_{(T,s)}^{u^*}, \mathbb{R}^d) W_1(\sigma_x^*(s), \sigma_x^*(t)) d\mu^*(T)(x) \leq L'_T |t - s| \end{aligned}$$

where $L'_T > 0$ is a uniform constant depending on the time and space Lipschitz constants of the flows of diffeomorphisms $(\Phi_{(T,t)}^{u^*}(\cdot))_{t \in [0, T]}$ and on L_U . Taking the supremum over all the 1-Lipschitz functions $\xi(\cdot, \cdot)$ and using the Kantorovich-Rubinstein duality (9) allows to conclude.

Finally, remark that for any $\xi \in C_c^\infty(\mathbb{R}^{2d}, \mathbb{R})$ it holds

$$\begin{aligned} \frac{d}{dt} \left[\int_{\mathbb{R}^{2d}} \xi(x, r) d\nu^*(t)(x, r) \right] &= \frac{d}{dt} \left[\int_{\mathbb{R}^d} \int_{\mathbb{R}^d} \xi(\Phi_{(T,t)}^{u^*}(x), r) d\sigma_x^*(t)(r) d\mu^*(T)(x) \right] \\ &= \int_{\mathbb{R}^d} \int_{\mathbb{R}^d} \langle \nabla_x \xi(\Phi_{(T,t)}^{u^*}(x), r), u^*(t, \Phi_{(T,t)}^{u^*}(x)) \rangle d\sigma_x^*(t)(r) d\mu^*(T)(x) \\ &\quad + \int_{\mathbb{R}^d} \int_{\mathbb{R}^d} \langle \nabla_r \xi(\Phi_{(T,t)}^{u^*}(x), r), -\text{D}_x u^*(t, \Phi_{(T,t)}^{u^*}(x))^\top r \rangle d\sigma_x^*(t)(r) d\mu^*(T)(x) \\ &= \int_{\mathbb{R}^{2d}} \left\langle \nabla_{(x,r)} \xi(x, r), \begin{pmatrix} u^*(t, x) \\ -\text{D}_x u^*(t, x)^\top r \end{pmatrix} \right\rangle d\nu^*(t)(x, r) \end{aligned}$$

which along with the fact that $\nu^*(T) = \nu_T^*(T) = (I_d \times (-\bar{\gamma}_\varphi^\circ(\cdot)))_{\#} \mu^*(T)$ achieves the proof. \square

²Namely, $\nu_T^*(t)$ is defined as the $\mu^*(T)$ -almost uniquely determined measure which has $\mu^*(T)$ as its first marginal and which disintegration is given by $\{\sigma_x^*(t)\}_x$ (see Definition 16).

We now show that the curve of measures $\nu^*(\cdot)$ defined in Lemma 25 is such that the map $\mathcal{K}_{\omega,\tau}(\cdot)$ defined by

$$\mathcal{K}_{\omega,\tau} : t \in [\tau, T] \mapsto \int_{\mathbb{R}^{2d}} \langle r, \mathcal{F}_t^{\omega,\tau} \circ \Phi_{(t,\tau)}^{u^*}(x) \rangle d\nu^*(t)(x, r), \quad (43)$$

is constant over $[\tau, T]$. We shall see in Step 4 that this is equivalent to the Pontryagin maximization condition (33).

Lemma 26. *The map $t \mapsto \mathcal{K}_{\omega,\tau}(t)$ defined in (43) is constant over $[\tau, T]$ for any couple of needle parameters (ω, τ) .*

Proof. Notice that by definition of $\nu^*(\cdot)$, the map $\mathcal{K}_{\omega,\tau}(\cdot)$ rewrites

$$\mathcal{K}_{\omega,\tau}(t) = \int_{\mathbb{R}^d} \int_{\mathbb{R}^d} \langle r, \mathcal{F}_t^{\omega,\tau} \circ \Phi_{(T,\tau)}^{u^*}(x) \rangle d\sigma_x^*(t)(r) d\mu^*(T)(x) \quad \text{for all } t \in [\tau, T]. \quad (44)$$

The maps $t \in [\tau, T] \mapsto \mathcal{F}_t^{\omega,\tau} \circ \Phi_{(T,\tau)}^{u^*}(x)$ and $t \in [\tau, T] \mapsto \sigma_x^*(t)$ are Lipschitz, uniformly with respect to $x \in \text{supp}(\mu^*(T))$. The integrand $(x, r) \mapsto \langle r, \mathcal{F}_t^{\omega,\tau} \circ \Phi_{(T,\tau)}^{u^*}(x) \rangle$ is bounded with respect to x and Lipschitz with respect to r , uniformly with respect to $t \in [\tau, T]$. Hence, $t \mapsto \mathcal{K}_{\omega,\tau}(t)$ is Lipschitz as well. It will therefore be constant provided that its derivative - which exists \mathcal{L}^1 -almost everywhere - is equal to zero.

Observe that, using formula (13) and the definition of \mathcal{V}^* in (25), it holds

$$\begin{aligned} \frac{d}{dt} \mathcal{K}_{\omega,\tau}(t) &= \int_{\mathbb{R}^d} \int_{\mathbb{R}^d} \langle r, \partial_t \mathcal{F}_t^{\omega,\tau} \circ \Phi_{(T,\tau)}^{u^*}(x) \rangle d\sigma_x^*(t)(r) d\mu^*(T)(x) \\ &\quad + \int_{\mathbb{R}^d} \int_{\mathbb{R}^d} \langle -D_x u^*(t, \Phi_{(T,t)}^{u^*}(x))^\top r, \mathcal{F}_t^{\omega,\tau} \circ \Phi_{(T,\tau)}^{u^*}(x) \rangle d\sigma_x^*(t)(r) d\mu^*(T)(x). \end{aligned} \quad (45)$$

We recall the characterization of $\partial_t \mathcal{F}_t^{\omega,\tau}(\cdot)$ given in (37) and plug it into (45). This implies that $\frac{d}{dt} \mathcal{K}_{\omega,\tau}(t) = 0$ for \mathcal{L}^1 -almost every times $t \in [\tau, T]$, and thus that $\mathcal{K}_{\omega,\tau}(\cdot)$ is constant over $[\tau, T]$. \square

Step 4 : Proof of the Pontryagin Maximum Principle for (\mathcal{P}_1)

We proved in Lemma 25 the existence of a constant $R \equiv R'_T > 0$ such that the solution $\nu^*(\cdot)$ to (40) satisfies $\text{supp}(\nu^*(\cdot)) \subset \overline{B_{2d}(0, R)}$. We accordingly define the infinite dimensional Hamiltonian $\mathbb{H} : (\nu, \omega) \in \mathcal{P}_c(\mathbb{R}^{2d}) \times U \mapsto \int_{\mathbb{R}^{2d}} \langle r, \omega(x) \rangle d\nu(x, r)$ of the system and the compactified Hamiltonian $\mathbb{H}_c(\cdot, \cdot)$ by (31).

In Lemma 26 we showed that, with this choice of forward-backward system (40), the map $\mathcal{K}_{\omega,\tau}(\cdot)$ defined in (43) is constant over $[\tau, T]$ for any choice of $\omega \in U$ and $\tau \in [0, T]$ Lebesgue point of $u^*(\cdot)$. This implies in particular that $\mathcal{K}_{\omega,\tau}(\tau) = \mathcal{K}_{\omega,\tau}(T)$. Since we proved in (39) that it holds

$$0 \leq \int_{\mathbb{R}^d} \langle \bar{\gamma}_\varphi^\circ(x), \mathcal{F}_T^{\omega,\tau} \circ \Phi_{(T,\tau)}^{u^*}(x) \rangle d\mu^*(T)(x) = -K_{\omega,\tau}(T),$$

we deduce that

$$\mathcal{K}_{\omega,\tau}(\tau) = \int_{\mathbb{R}^{2d}} \langle r, \omega(x) - u^*(\tau, x) \rangle d\nu^*(\tau)(x, r) \leq 0 \quad \text{for all } \omega \in U \text{ and } \tau \in [0, T] \text{ Lebesgue point of } u^*(\cdot).$$

Recalling that \mathcal{L}^1 -almost $\tau \in [0, T]$ is a Lebesgue point for an L^1 function defined over the real line in the Bochner sense (see e.g. [16, Chapter 2, Theorem 9]), we recover the infinite dimensional maximization condition (33) :

$$\mathbb{H}_c(\nu^*(t), u^*(t)) = \max_{\omega \in U} [\mathbb{H}_c(\nu^*(t), \omega)] \quad \text{for } \mathcal{L}^1\text{-almost every } t \in [0, T].$$

Invoking the C^1 regularity of the elements of U , it can be seen using Proposition 2 that the minimal selection $\partial_\nu^\circ \mathbb{H}_c(\nu^*(t), u^*(t))$ in the extended subdifferential of $\mathbb{H}_c(\cdot, u^*(t))$ exists at $\nu^*(t) \in \mathcal{P}(\overline{B_{2d}(0, R)})$ for \mathcal{L}^1 -almost every $t \in [0, T]$ and that it is induced by the map

$$\nabla_\nu \mathbb{H}_c(\nu^*(t), u^*(t)) : (x, r) \in \text{supp}(\nu^*(t)) \mapsto \begin{pmatrix} D_x u^*(t, x)^\top r \\ u^*(t, x) \end{pmatrix}.$$

Therefore, we recognize the Wasserstein Hamiltonian structure $\mathcal{V}^*(t, \cdot, \cdot) = \mathbb{J}_{2d} \nabla_\nu \mathbb{H}_c(\nu^*(t), u^*(t))(\cdot, \cdot)$ for \mathcal{L}^1 -almost every $t \in [0, T]$ where \mathbb{J}_{2d} is the symplectic matrix in \mathbb{R}^{2d} . This ends our proof of Theorem 6.

3.2 The general Pontryagin Maximum Principle

After having exhibited the main mechanisms of our proof for the Pontryagin Maximum Principle for the simplified problem (\mathcal{P}_1) , we are ready to tackle the general case proposed in (\mathcal{P}) . Problem (\mathcal{P}) is a generalization of (\mathcal{P}_1) in the sense that we add a general running cost $L(\cdot, \cdot)$ and a general non-local interaction vector field $v[\cdot](\cdot, \cdot)$.

Step 1 : Needle-like variations in the non-local case

As in Section 3.1, let us consider an optimal pair control-trajectory $(u^*(\cdot), \mu^*(\cdot))$, a Lebesgue point $\tau \in [0, T]$ of $u^*(\cdot)$ and an element $\omega \in U$. We introduce again the needle-like variation $\tilde{u}_\epsilon^{\omega, \tau}(\cdot)$ of $u^*(\cdot)$ with parameters (ω, τ, ϵ) for $\epsilon \in [0, \bar{\epsilon}]$, as defined in (34). Notice that this time, τ is a Lebesgue point for $t \mapsto v[\mu^*(t)](t, \cdot) + u^*(t, \cdot)$.

In keeping with the notations introduced in (16) for flows associated to transport PDEs with non-local velocities, the family of perturbed measures $\epsilon \in [0, \bar{\epsilon}] \mapsto \tilde{\mu}_t(\epsilon)$ are defined for all times $t \in [\tau, T]$ by

$$\tilde{\mu}_t(\epsilon) = \Phi_{(\tau, t)}^{v, u^*}[\tilde{\mu}_\tau(\epsilon)] \circ \Phi_{(\tau - \epsilon, \tau)}^{v, \omega}[\mu^*(\tau - \epsilon)] \circ \Phi_{(t, \tau - \epsilon)}^{v, u^*}[\mu^*(t)](\cdot) \# \mu^*(t).$$

One can readily check that under the sub-linearity and regularity hypotheses imposed in **(U)** and **(F)**, there exists again a constant $\bar{R}_T > 0$ such that $\text{supp}(\tilde{\mu}_t(\epsilon)) \subset \bar{B}(0, \bar{R}_T)$ for all $(t, \epsilon) \in [0, T] \times [0, \bar{\epsilon}]$.

We now derive in Lemma 27 the perturbation stemming from the needle-like variation. We prove therein a result akin to Lemma 24 giving a precise ODE-type characterization of this perturbation. To do so, we use the results of Theorem 5 concerning the directional derivatives of the non-local flow combined to the classical result stated in Lemma 24 and the definition of needle-like variation.

Lemma 27 (Perturbation induced by a needle-like variation in the non-local case). *Let $(u^*(\cdot), \mu^*(\cdot))$ be an optimal pair control-trajectory for problem (\mathcal{P}) and $\tilde{u}_\epsilon(\cdot)$ be the needle-like perturbation of $u^*(\cdot)$ as introduced in (34).*

Then, there exists for all times $t \in [\tau, T]$ a family of functions $\mathcal{G}_t^{\omega, \tau}(\cdot, \cdot) \in \text{Lip}((-\bar{\epsilon}, \bar{\epsilon}), C^0(\mathbb{R}^d, \mathbb{R}^d))$ such that they are C^1 -diffeomorphisms over $\bar{B}(0, R_T)$ for all $\epsilon \geq 0$ and it holds

$$\tilde{\mu}_t(\epsilon) = \mathcal{G}_t^{\omega, \tau}(\epsilon, \cdot) \# \mu^*(t).$$

Besides, there exists a constant $R_T^\Phi > 0$ depending on R_T, L_U and $v[\cdot](\cdot, \cdot)$ such that for all $(t, \epsilon) \in [\tau, T] \times (-\bar{\epsilon}, \bar{\epsilon})$ it holds $\text{supp}(\mathcal{G}_t^{\omega, \tau}(\epsilon, \cdot) \# \mu^(t)) \subset \bar{B}(0, R_T^\Phi)$.*

This family of maps satisfies the following Taylor expansion for all $t \in [\tau, T]$ with respect to the $L^2(\mathbb{R}^d, \mathbb{R}^d; \mu^(t))$ norm :*

$$\mathcal{G}_t^{\omega, \tau}(\epsilon, \cdot) = I_d + \epsilon \mathcal{F}_t^{\omega, \tau} \circ \Phi_{(t, \tau)}^{v, u^*}[\mu^*(t)](\cdot) + o(\epsilon),$$

with

$$\mathcal{F}_t^{\omega, \tau} : x \in \text{supp}(\mu^*(\tau)) \mapsto D_x \Phi_{(\tau, t)}^{v, u^*}[\mu^*(\tau)](x) \cdot [\omega(x) - u^*(\tau, x)] + w_\Phi^{\omega, \tau}(t, x)$$

where $w_\Phi^{\omega, \tau}(t, x)$ is the derivative at $\epsilon = 0$ of the map $\epsilon \in (-\bar{\epsilon}, \bar{\epsilon}) \mapsto \Phi_{(\tau, t)}^{v, u^*}[\tilde{\mu}_\tau(\epsilon)](x)$ as described in Theorem 5.

Moreover, the map $(t, x) \in [\tau, T] \times \text{supp}(\mu^*(\tau)) \mapsto \mathcal{F}_t^{\omega, \tau}(x)$ is the unique solution of the Cauchy problem

$$\begin{cases} \partial_t \mathcal{F}_t^{\omega, \tau}(x) = \left[D_x u^* \left(t, \Phi_{(\tau, t)}^{v, u^*}[\mu^*(\tau)](x) \right) + D_x v[\mu^*(t)] \left(t, \Phi_{(\tau, t)}^{v, u^*}[\mu^*(\tau)](x) \right) \right] \cdot \mathcal{F}_t^{\omega, \tau}(x) \\ \quad + \int_{\mathbb{R}^d} \Pi^\circ \left(t, \Phi_{(\tau, t)}^{v, u^*}[\mu^*(\tau)](x) \right) \left(\Phi_{(\tau, t)}^{v, u^*}[\mu^*(\tau)](y) \right) \cdot \mathcal{F}_t^{\omega, \tau}(y) d\mu^*(\tau)(y) \\ \mathcal{F}_\tau^{\omega, \tau}(x) = \omega(x) - u^*(\tau, x). \end{cases} \quad (46)$$

Proof. We start by computing the measures $\tilde{\mu}_\tau(\epsilon)$ as a function of $\mu^*(\tau)$ for all $\epsilon \in [0, \bar{\epsilon}]$. By definition of the needle-like variation, it holds

$$\tilde{\mu}_\tau(\epsilon) = \Phi_{(\tau - \epsilon, \tau)}^{v, \omega}[\mu^*(\tau - \epsilon)] \circ \Phi_{(\tau, \tau - \epsilon)}^{v, u^*}[\mu^*(\tau)](\cdot) \# \mu^*(\tau)$$

Using Lebesgue's Differentiation Theorem, we obtain the following expansions at the first order with respect to ϵ :

$$\begin{aligned}\Phi_{(\tau-\epsilon,\tau)}^{v,\omega}[\mu^*(\tau-\epsilon)](y) &= y + \int_{\tau-\epsilon}^{\tau} \left[v[\tilde{\mu}_t(\epsilon)] \left(t, \Phi_{(\tau-\epsilon,t)}^{v,\omega}[\mu^*(\tau-\epsilon)](y) \right) + \omega \left(\Phi_{(\tau-\epsilon,t)}^{v,\omega}[\mu^*(\tau-\epsilon)](y) \right) \right] dt, \\ &= y + \epsilon (v[\mu^*(\tau)](\tau, y) + \omega(y)) + o(\epsilon),\end{aligned}$$

as well as

$$\begin{aligned}\Phi_{(\tau,\tau-\epsilon)}^{v,u^*}[\mu^*(\tau)](y) &= y - \int_{\tau-\epsilon}^{\tau} \left[v[\mu^*(t)] \left(t, \Phi_{(t,\tau-\epsilon)}^{v,u^*}[\mu^*(\tau)](y) \right) + u^* \left(t, \Phi_{(t,\tau-\epsilon)}^{v,u^*}[\mu^*(\tau)](y) \right) \right] dt, \\ &= y - \epsilon (v[\mu^*(\tau)](\tau, y) + u^*(\tau, y)) + o(\epsilon).\end{aligned}$$

Chaining these two expressions together and recalling that $\omega(\cdot)$ and $v[\mu^*(\tau)](\tau, \cdot)$ are C^1 -smooth, it holds

$$\Phi_{(\tau-\epsilon,\tau)}^{v,\omega}[\mu^*(\tau-\epsilon)] \circ \Phi_{(\tau,\tau-\epsilon)}^{v,u^*}[\mu^*(\tau)](y) = y + \epsilon [\omega(y) - u^*(\tau, y)] + o(\epsilon)$$

and we deduce the expression that will prove useful in the sequel

$$\tilde{\mu}_\tau(\epsilon) = (I_d + \epsilon [\omega(\cdot) - u^*(\tau, \cdot)] + o(\epsilon))_{\#} \mu^*(\tau). \quad (47)$$

We now want to obtain a similar expression but at some time $t \in [\tau, T]$. First, recall that $\tilde{\mu}_t(\epsilon) = \mathcal{G}_t^{\omega,\tau}(\epsilon, \cdot)_{\#} \mu^*(t)$ where

$$\mathcal{G}_t^{\omega,\tau}(\epsilon, \cdot) : x \in \text{supp}(\mu^*(t)) \mapsto \Phi_{(\tau,t)}^{v,u^*}[\tilde{\mu}_\tau(\epsilon)] \circ \Phi_{(\tau-\epsilon,\tau)}^{v,\omega}[\mu^*(\tau-\epsilon)] \circ \Phi_{(\tau,\tau-\epsilon)}^{v,u^*}[\mu^*(\tau)] \circ \Phi_{(t,\tau)}^{v,u^*}[\mu^*(t)](x). \quad (48)$$

By our previous computation, one has the following pointwise expansion

$$\begin{aligned}& \Phi_{(\tau,t)}^{v,u^*}[\tilde{\mu}_\tau(\epsilon)] \circ \Phi_{(\tau-\epsilon,\tau)}^{v,\omega}[\mu^*(\tau-\epsilon)] \circ \Phi_{(\tau,\tau-\epsilon)}^{v,u^*}[\mu^*(\tau)] \circ \Phi_{(t,\tau)}^{v,u^*}[\mu^*(t)](\cdot) \\ &= \Phi_{(\tau,t)}^{v,u^*}[\tilde{\mu}_\tau(\epsilon)] \circ \left(\Phi_{(t,\tau)}^{v,u^*}[\mu^*(\tau)](\cdot) + \epsilon \left[\omega \left(\Phi_{(t,\tau)}^{v,u^*}[\mu^*(\tau)](\cdot) \right) - u^* \left(\tau, \Phi_{(t,\tau)}^{v,u^*}[\mu^*(\tau)](\cdot) \right) \right] + o(\epsilon) \right) \\ &= \Phi_{(\tau,t)}^{v,u^*}[\tilde{\mu}_\tau(\epsilon)] \left(\Phi_{(t,\tau)}^{v,u^*}[\mu^*(\tau)](\cdot) \right) \\ &+ \epsilon D_x \Phi_{(\tau,t)}^{v,u^*}[\mu^*(\tau)] \left(\Phi_{(t,\tau)}^{v,u^*}[\mu^*(\tau)](\cdot) \right) \left[\omega \left(\Phi_{(t,\tau)}^{v,u^*}[\mu^*(\tau)](\cdot) \right) - u^* \left(\tau, \Phi_{(t,\tau)}^{v,u^*}[\mu^*(\tau)](\cdot) \right) \right] + o(\epsilon).\end{aligned} \quad (49)$$

since $\tilde{\mu}_\tau(\epsilon) \xrightarrow[\epsilon \downarrow 0]{W_1} \mu^*(\tau)$ and we are only interested in a Taylor expansion at the first order in ϵ .

It then remains to compute the $O(\epsilon)$ term in (49). Due to Theorem 5, the derivative of the non-local flow along directions induced by Lipschitz families of continuous and bounded maps exists. It can moreover be characterized explicitly through (23). Recalling (47), this condition translates into

$$\Phi_{(\tau,t)}^{v,u^*}[\tilde{\mu}_\tau(\epsilon)](y) = \Phi_{(\tau,t)}^{v,u^*}[\mu^*(\tau)](y) + \epsilon w_{\Phi}^{\omega,\tau}(t, y) + o(\epsilon),$$

where $w_{\Phi}^{\omega,\tau}(t, y)$ is defined through (23) is the case where the non-local velocity field is given by $(t, x) \mapsto v[\mu^*(t)](t, x) + u^*(t, x)$.

Thus, we proved the pointwise Taylor expansion at the first order with ϵ :

$$\mathcal{G}_t^{\omega,\tau}(\epsilon, x) = x + \epsilon \mathcal{F}_t^{\omega,\tau} \circ \Phi_{(t,\tau)}^{u^*,v}[\mu^*(t)](x) + o(\epsilon) \quad \text{for } \mu^*(t)\text{-almost every } x \in \mathbb{R}^d,$$

where

$$\mathcal{F}_t^{\omega,\tau} : x \in \text{supp}(\mu^*(\tau)) \mapsto D_x \Phi_{(\tau,t)}^{v,u^*}[\mu^*(\tau)](x) \cdot [\omega(x) - u^*(\tau, x)] + w_{\Phi}^{\omega,\tau}(t, x) \quad (50)$$

A standard application of Proposition 13-(iii) shows that this expansion holds in $L^2(\mathbb{R}^d, \mathbb{R}^d; \mu^*(t))$. One can then extend $\mathcal{G}_t^{\omega,\tau}(\cdot, \cdot)$ to $(-\bar{\epsilon}, \bar{\epsilon})$ while preserving this expansion around $\epsilon = 0$ by defining e.g.

$$\mathcal{G}_t^{\omega,\tau}(\epsilon, \cdot) \equiv I_d + \epsilon \mathcal{F}_t^{\omega,\tau} \circ \Phi_{(\tau,t)}^{v,u^*}[\mu^*(\tau)](\cdot) \quad \text{for } \epsilon \in (-\bar{\epsilon}, 0].$$

The existence of a constant R_T^{Φ} depending on R_T, L_U and $v[\cdot](\cdot, \cdot)$ such that $\text{supp}(\mathcal{G}_t^{\omega,\tau}(\epsilon, \cdot)_{\#} \mu^*(t)) \subset \overline{B(0, R_T^{\Phi})}$ follows from hypotheses **(F)** and **(B)**, which ensure the continuity and boundedness of the perturbation functions over $\overline{B(0, \tilde{R}_T)}$.

We finally prove the counterpart of Lemma 24 providing an ODE-type characterization for the perturbation induced by the needle-like variation in the non-local case. Recalling the definition of $(t, x) \mapsto \mathcal{F}_t^{\omega, \tau}(x)$ given in (50) and summing the ODE-type characterization of $t \mapsto w_{\Phi}^{\omega, \tau}(t, \cdot)$ and $D_x \Phi_{(\tau, \cdot)}^{v, u^*}[\mu^*(\tau)](t) \cdot [\omega(\cdot) - u^*(\tau, \cdot)]$, we recover

$$\begin{cases} \partial_t \mathcal{F}_t^{\omega, \tau}(x) = \left[D_x u^* \left(t, \Phi_{(\tau, t)}^{v, u^*}[\mu^*(\tau)](x) \right) + D_x v[\mu^*(t)] \left(t, \Phi_{(\tau, t)}^{v, u^*}[\mu^*(\tau)](x) \right) \right] \cdot \mathcal{F}_t^{\omega, \tau}(x) \\ \quad + \int_{\mathbb{R}^d} \mathbb{I}^\circ \left(t, \Phi_{(\tau, t)}^{v, u^*}[\mu^*(\tau)](x) \right) \left(\Phi_{(\tau, t)}^{v, u^*}[\mu^*(\tau)](y) \right) \cdot \mathcal{F}_t^{\omega, \tau}(y) d\mu^*(\tau)(y) \\ \mathcal{F}_\tau^{\omega, \tau}(x) = \omega(x) - u^*(\tau, x). \end{cases}$$

This concludes our proof. \square

In the development of Steps 2, 3 and 4, we do not need to take into account the explicit dependence of the flow with respect to its starting measure. We shall henceforth write $\Phi_{(\cdot, \cdot)}^{v, u^*}(\cdot) \equiv \Phi_{(\cdot, \cdot)}^{v, u^*}[\mu^*(\cdot)](\cdot)$ for clarity and conciseness.

Step 2 : First-order optimality condition

In the framework of Problem (\mathcal{P}) , the optimality of $u^*(\cdot)$ writes

$$\begin{aligned} \frac{\varphi(\tilde{\mu}_T(\epsilon)) - \varphi(\mu^*(T))}{\epsilon} + \frac{1}{\epsilon} \int_{\tau-\epsilon}^T [L(\tilde{\mu}_t(\epsilon), \omega) - L(\mu^*(t), u^*(t))] dt \\ + \frac{1}{\epsilon} \int_\tau^T [L(\tilde{\mu}_t(\epsilon), u^*(t)) - L(\mu^*(t), u^*(t))] dt \geq 0 \quad \text{for all } \epsilon \in [0, \bar{\epsilon}]. \end{aligned} \quad (51)$$

The first order perturbation corresponding to the final cost $\varphi(\cdot)$ has already been treated in (38)-(39), Section 3.1. We study the integral terms arising from the running cost. Remark first that it holds

$$\lim_{\epsilon \downarrow 0} \left[\frac{1}{\epsilon} \int_{\tau-\epsilon}^T [L(\tilde{\mu}_t(\epsilon), \omega) - L(\mu^*(t), u^*(t))] dt \right] = L(\mu^*(\tau), \omega) - L(\mu^*(\tau), u^*(\tau)),$$

by the Lebesgue Differentiation Theorem, since $\tilde{\mu}_t(\epsilon) \xrightarrow{W_1} \mu^*(t)$ as $\epsilon \downarrow 0$ for all $t \in [0, T]$ and since τ is a Lebesgue point of $u^*(\cdot)$.

Equivalently to the proof of the PMP for Problem (\mathcal{P}_1) , the perturbed measures are uniformly supported in a compact set. Thus, under hypotheses **(L)** and recalling that the function $\epsilon \in (-\bar{\epsilon}, \bar{\epsilon}) \mapsto L(\tilde{\mu}_t(\epsilon), u^*(t))$ is differentiable at $\epsilon = 0$ for \mathcal{L}^1 -almost every $t \in [\tau, T]$ by hypothesis **(D)**, the chain rule of Proposition 21 can be applied to the running cost to obtain

$$\lim_{\epsilon \downarrow 0} \left[\frac{1}{\epsilon} [L(\tilde{\mu}_t(\epsilon), u^*(t)) - L(\mu^*(t), u^*(t))] \right] = \int_{\mathbb{R}^{2d}} \langle \bar{\gamma}_L^\circ(t, x), \mathcal{F}_t^{\omega, \tau} \circ \Phi_{(t, \tau)}^{v, u^*}(x) \rangle d\mu^*(t)(x), \quad (52)$$

where $\bar{\gamma}_L^\circ(t, \cdot) \in L^2(\mathbb{R}^d, \mathbb{R}^d; \mu^*(t))$ is the barycenter of $\mathcal{D}_\mu^\circ L(\mu^*(t), u^*(t))$ for \mathcal{L}^1 -almost every $t \in [0, T]$.

Moreover, the uniform compactness of the supports of the perturbed measures and hypothesis **(L)** imply that the left hand side in (52) is uniformly bounded by a function in $L^1([0, T], \mathbb{R}_+)$ for any $\epsilon \in (0, \bar{\epsilon})$. Therefore, by an application of Lebesgue Dominated Convergence Theorem, it holds

$$\lim_{\epsilon \downarrow 0} \left[\frac{1}{\epsilon} \int_\tau^T [L(\tilde{\mu}_t(\epsilon), u^*(t)) - L(\mu^*(t), u^*(t))] dt \right] = \int_\tau^T \int_{\mathbb{R}^{2d}} \langle \bar{\gamma}_L^\circ(t, x), \mathcal{F}_t^{\omega, \tau} \circ \Phi_{(t, \tau)}^{v, u^*}(x) \rangle d\mu^*(t)(x) dt.$$

Thus, the optimality of $(u^*(\cdot), \mu^*(\cdot))$ translates into the first-order condition

$$\begin{aligned} \int_{\mathbb{R}^{2d}} \langle \bar{\gamma}_\varphi^\circ(x), \mathcal{F}_T^{\omega, \tau} \circ \Phi_{(T, \tau)}^{v, u^*}(x) \rangle d\mu^*(T)(x) + [L(\mu^*(\tau), \omega) - L(\mu^*(\tau), u^*(\tau))] \\ + \int_\tau^T \int_{\mathbb{R}^{2d}} \langle \bar{\gamma}_L^\circ(t, x), \mathcal{F}_t^{\omega, \tau} \circ \Phi_{(t, \tau)}^{v, u^*}(x) \rangle d\mu^*(t)(x) dt \geq 0, \end{aligned} \quad (53)$$

for any couple of needle parameters (ω, τ) .

Step 3 : Backward dynamics and Pontryagin maximization condition

We now build a solution $\nu^*(\cdot) \in \text{Lip}([0, T], \mathcal{P}_c(\mathbb{R}^{2d}))$ to the system of continuity equations

$$\begin{cases} \partial_t \nu^*(t) + \nabla \cdot (\mathcal{V}^*[\nu^*(t)](t, \cdot, \cdot) \nu^*(t)) = 0 & \text{in } [0, T] \times \mathbb{R}^{2d}, \\ \pi_{\#}^1 \nu^*(t) = \mu^*(t) & \text{for all } t \in [0, T], \\ \nu^*(T) = (I_d \times (-\bar{\gamma}_\varphi^\circ))_{\#} \mu^*(T), \end{cases} \quad (54)$$

associated to the non-local vector field $\mathcal{V}^*[\nu^*(t)] : (t, x, r) \mapsto (v[\pi_{\#}^1 \nu^*(t)](t, x) + u^*(t, x), \bar{\gamma}_L^\circ(t, x) - \mathbb{I}_v^\circ[\nu^*(t)](t, x) - D_x u^*(t, x)^\top r - D_x v[\mu^*(t)](t, x)^\top r)$ where $\mathbb{I}_v^\circ[\cdot](\cdot, \cdot)$ is defined by

$$\mathbb{I}_v^\circ[\cdot](\cdot, \cdot) : (\nu, t, x) \in \mathcal{P}_c(\mathbb{R}^d) \times [0, T] \times \text{supp}(\pi_{\#}^1 \nu) \mapsto \int_{\mathbb{R}^{2d}} \left(\mathbb{I}_{(t, y)}^\circ(x) \right)^\top p \, d\nu(y, p) \quad (55)$$

with $\mathbb{I}_{(\cdot, \cdot)}^\circ(\cdot)$ defined as in Theorem 1.

As in Lemma 25 of Section 3.1, we build a solution of (54) by making use of the cascade structure. We then show that this solution $\nu^*(\cdot)$ is such that the map $\mathcal{K}_{\omega, \tau}(\cdot)$ defined in this context by

$$\begin{aligned} \mathcal{K}_{\omega, \tau} : t \in [\tau, T] \mapsto & \int_{\mathbb{R}^{2d}} \langle r, \mathcal{F}_t^{\omega, \tau} \circ \Phi_{(t, \tau)}^{v, u^*}(x) \rangle d\nu^*(t)(x, r) + [L(\mu^*(\tau), u^*(\tau)) - L(\mu^*(\tau), \omega)] \\ & - \int_{\tau}^t \int_{\mathbb{R}^{2d}} \langle \bar{\gamma}_L^\circ(t, x), \mathcal{F}_s^{\omega, \tau} \circ \Phi_{(s, \tau)}^{v, u^*}(x) \rangle d\mu^*(s)(x) ds \end{aligned} \quad (56)$$

is constant over $[\tau, T]$.

Lemma 28 (Well-posedness of solutions of (54)). *Let $\mu^*(\cdot)$ be the optimal trajectory for (\mathcal{P}) generated by the optimal control $u^*(\cdot) \in \mathcal{U}$. For $\mu^*(T)$ -almost every $x \in \mathbb{R}^d$, we consider the family of flows of diffeomorphisms $(\Phi_{(T, t)}^{B, x}(\cdot))_{t \leq T}$ associated to the Cauchy problems*

$$\begin{cases} \partial_t w_x(t, r) = \bar{\gamma}_L^\circ(t, \Phi_{(T, t)}^{v, u^*}(x)) - D_x v[\mu^*(t)](t, \Phi_{(T, t)}^{v, u^*}(x))^\top w_x(t, r) - Du^*(t, \Phi_{(T, t)}^{v, u^*}(x))^\top w_x(t, r) \\ \quad - \int_{\mathbb{R}^{2d}} \mathbb{I}_{(t, \Phi_{(T, t)}^{v, u^*}(y))}^\circ \left(\Phi_{(T, t)}^{v, u^*}(x) \right)^\top w_y(t, p) \, d(I_d \times (-\bar{\gamma}_\varphi^\circ))_{\#} \mu^*(T)(y, p), \\ w_x(T, r) = -\bar{\gamma}_\varphi^\circ(x). \end{cases} \quad (57)$$

We define the curves of measures $\sigma_x^* : t \mapsto \Phi_{(T, t)}^{B, x}(\cdot)_{\#} \mu^*(T)$ and denote by $\mathcal{V}_x^*[\nu_T^*(\cdot)](\cdot, \cdot)$ the corresponding non-local vector fields describing their evolution.

Define $\nu^* : t \mapsto (\Phi_{(T, t)}^{u^*}(\cdot), I_d)_{\#} \nu_T^*(t)$ where $\nu_T^*(t) = \int \sigma_x^*(t) d\mu^*(T)(x)$. Then, $\nu^*(\cdot)$ solves (54). Moreover, there exists two constants $R'_T, L'_T > 0$ such that

$$\text{supp}(\nu^*(t)) \subset \overline{B_{2d}(0, R'_T)} \quad \text{and} \quad W_1(\nu^*(t), \nu^*(s)) \leq L'_T |t - s| \quad \text{for all } s, t \in [0, T].$$

Proof. We start by proving that the non-local velocity in the right hand side of (57) satisfies hypotheses **(H')**. The uniform Lipschitzianity imposed in hypotheses **(U)** and **(F)** on the controls and the non-local vector field $v[\cdot](\cdot, \cdot)$ along with the requirement in **(B)** that $t \mapsto \bar{\gamma}_L^\circ(t, \cdot)$ be uniformly bounded give the Lipschitzianity and the sub-linearity in space. The Lipschitzianity in the W_1 -metric of the non-local part of the vector field follows from Kantorovich-Rubinstein duality and the fact that we are integrating the product of a bounded term and of a linear term.

The proof that the curve $\nu^*(\cdot)$ is uniformly compactly supported in a ball of radius R_T , Lipschitz in the W_1 -metric with a constant L'_T and that it solves (54) is completely analogous to Lemma 25 \square

Lemma 29. *The map $t \mapsto \mathcal{K}_{\omega, \tau}(t)$ defined in (56) is constant over $[\tau, T]$ for any couple of needle parameters (ω, τ) .*

Proof. This proof follows the same steps as in the proof of Lemma 26, the difference lying in the fact that the flows $(\Phi_{(0, t)}^{v, u^*}(\cdot))_{t \in [0, T]}$ are associated to the non-local PDE. It can be verified again that $t \mapsto \mathcal{K}_{\omega, \tau}(t)$ is Lipschitz in this context. We compute $\frac{d}{dt} \mathcal{K}_{\omega, \tau}(\cdot)$ using (13) as in (45) while plugging in the expressions for $\mathcal{F}_t^{\omega, \tau}(\cdot)$ and its time-derivative provided by Lemma 27.

$$\begin{aligned}
\frac{d}{dt}\mathcal{K}_{\omega,\tau}(t) &= \int_{\mathbb{R}^d} \int_{\mathbb{R}^d} \left\langle r, \partial_t \mathcal{F}_t^{\omega,\tau} \circ \Phi_{(T,\tau)}^{v,u^*}(x) \right\rangle d\sigma_x^*(t)(r) d\mu^*(T)(x) \\
&+ \int_{\mathbb{R}^d} \int_{\mathbb{R}^d} \left\langle \mathcal{V}_x^*[\nu_T^*(t)](t,r), \mathcal{F}_t^{\omega,\tau} \circ \Phi_{(T,\tau)}^{v,u^*}(x) \right\rangle d\sigma_x^*(t)(r) d\mu^*(T)(x) \\
&- \int_{\mathbb{R}^{2d}} \langle \tilde{\gamma}_L^\circ(t, \Phi_{(T,t)}^{v,u^*}(x)), \mathcal{F}_t^{\omega,\tau} \circ \Phi_{(T,\tau)}^{v,u^*}(x) \rangle d\mu^*(T)(x) \\
&= \int_{\mathbb{R}^{2d}} \left\langle r, \int_{\mathbb{R}^d} \Pi^\circ_{(t, \Phi_{(T,t)}^{v,u^*}(x))} \left(\Phi_{(T,t)}^{v,u^*}(y) \right) \mathcal{F}_t^{\omega,\tau} \circ \Phi_{(T,\tau)}^{v,u^*}(x) d\mu^*(T)(y) \right\rangle d\nu_T^*(t)(x,r) \\
&- \int_{\mathbb{R}^{2d}} \left\langle \int_{\mathbb{R}^{2d}} \Pi^\circ_{(t, \Phi_{(T,t)}^{v,u^*}(y))} \left(\Phi_{(T,t)}^{v,u^*}(x) \right)^\top p d\nu_T^*(t)(y,p), \mathcal{F}_t^{\omega,\tau} \circ \Phi_{(T,\tau)}^{v,u^*}(x) \right\rangle d\nu_T^*(t)(x,r) \\
&= 0
\end{aligned}$$

by plugging in the expressions of $\partial_t \mathcal{F}_t^{\omega,\tau}(\cdot)$ and $\mathcal{V}_x^*[\nu_T^*(t)](t, \cdot)$. The two quantities are shown to be equal due to the uniform boundedness of the integrands given by **(B)** and Fubini-Tonelli theorem. This altogether leads to $\frac{d}{dt}\mathcal{K}_{\omega,\tau}(\cdot) = 0$ and thus to $\mathcal{K}_{\omega,\tau}(\cdot)$ being constant over $[\tau, T]$. \square

Step 4 : Proof of the Pontryagin Maximum Principle for (\mathcal{P})

We proved in Lemma 28 that there exists a curve $\nu^* \in \text{Lip}([0, T], \mathcal{P}_c(\mathbb{R}^{2d}))$ solution of (54) along with a constant $R \equiv R'_T > 0$ such that $\text{supp}(\nu^*(\cdot)) \subset \overline{B_{2d}(0, R)}$. The non-local velocity field $\mathcal{V}^*[\nu^*(\cdot)](\cdot, \cdot, \cdot)$ is defined for $\mathcal{L}^1 \times \nu^*(\cdot)$ -almost every $(t, x, r) \in [0, T] \times \overline{B_{2d}(0, R)}$ by

$$\mathcal{V}^*[\nu^*(t)](t, x, r) \left(\begin{array}{c} \tilde{\gamma}_L^\circ(t, x) - D_x u^*(t, x)^\top r - D_x v[\pi_{\#}^1 \nu^*(t)](t, x)^\top r - \Pi_v^\circ[\pi_{\#}^1 \nu^*(t)](t, x) \\ v[\pi_{\#}^1 \nu^*(t)](t, x) + u^*(t, x) \end{array} \right).$$

We define the infinite dimensional Hamiltonian $\mathbb{H}(\cdot, \cdot, \cdot)$ of the system by

$$\mathbb{H} : (t, \nu, \omega) \in [0, T] \times \mathcal{P}_c(\mathbb{R}^{2d}) \times U \mapsto \int_{\mathbb{R}^{2d}} \langle r, \omega(x) \rangle d\nu(x, r) - L(\pi_{\#}^1 \nu, \omega).$$

along with its compactification $\mathbb{H}_c(\cdot, \cdot, \cdot)$ given by (3).

Furthermore, we proved in Lemma 29 that the solution $\nu^*(\cdot)$ that we built is such that the map $\mathcal{K}_{\omega,\tau}(\cdot)$ defined in (56) is constant over $[\tau, T]$ for any couple of needle parameters (ω, τ) . Hence, it holds in particular that $\mathcal{K}_{\omega,\tau}(\tau) = \mathcal{K}_{\omega,\tau}(T)$ which is a non-positive quantity by the first-order optimality condition (53). This fact implies that

$$\int_{\mathbb{R}^{2d}} \langle r, \omega(x) - u^*(\tau, x) \rangle d\nu^*(\tau)(x, r) - [L(\mu^*(t), \omega) - L(\mu^*(t), u^*(t))] \leq 0,$$

for all $\omega \in U$ and $\tau \in [0, T]$ Lebesgue point of $v[\mu^*(\cdot)](\cdot, \cdot) + u^*(\cdot)$. This inequality rewrites as the Pontryagin Maximization condition (5) :

$$\mathbb{H}_c(t, \nu^*(t), u^*(t)) = \max_{\omega \in U} [\mathbb{H}_c(t, \nu^*(t), \omega)] \quad \text{for } \mathcal{L}^1\text{-almost every } t \in [0, T].$$

Moreover, one recognizes the pseudo-Hamiltonian structure $\mathcal{V}^*[\nu^*(t)](t, x, r) = \mathbb{J}_{2d} \tilde{\nabla}_\nu \mathbb{H}_c(t, \nu^*(t), u^*(t))$ for $\mathcal{L}^1 \times \nu^*(\cdot)$ -almost every $(t, x, r) \in [0, T] \times \overline{B_{2d}(0, R)}$ where the map $\tilde{\nabla}_\nu \mathbb{H}_c(t, \nu^*(t), u^*(t))(\cdot, \cdot)$ is precisely the non-local velocity field $\mathcal{V}^*[\nu^*](t, \cdot, \cdot)$ for \mathcal{L}^1 -almost every $t \in [0, T]$. This concludes our proof of the Pontryagin Maximum Principle for (\mathcal{P}) .

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